Caveolin-1: a multifaceted driver of breast cancer progression and its application in clinical treatment

Abstract: Human breast cancer is one of the most frequent cancer diseases and causes of death among female population worldwide. It appears at a high incidence and has a high malignancy, mortality, recurrence rate and poor prognosis. Caveolin-1 (Cav1) is the main component of caveolae and participates in various biological events. More and more experimental studies have shown that Cav1 plays a critical role in the progression of breast cancer including cell proliferation, apoptosis, autophagy, invasion, migration and breast cancer metastasis. Besides, Cav1 has been found to be involved in chemotherapeutics and radiotherapy resistance, which are still the principal problems encountered in clinical breast cancer treatment. In addition, stromal Cav1 may be a potential indicator for breast cancer patients’ prognosis. In the current review, we cover the state-of-the-art study, development and progress on Cav1 and breast cancer, altogether describing the role of Cav1 in breast cancer progression and application in clinical treatment, in the hope of providing a basis for further research and promoting CAV1 gene as a potential target to diagnose and treat aggressive breast cancers.

Keywords: breast cancer, caveolin-1, migration, metastasis, prognosis, invasion

Introduction
Breast cancer is a common malignant disease among female population worldwide and is characterized by the highest cancer incidence, high recurrence rate, morbidity, mortality and poor prognosis. Breast cancer tumorigenesis is a multi-step process including proliferation, apoptosis, autophagy, invasion, migration, metastasis and drug resistance. According to pathological characteristics, human breast cancer can be divided into non-invasive breast cancer (eg, Paget disease of the breast), invasive breast carcinoma of special type (eg, invasive apocrine carcinoma, invasive micropapillary carcinoma), invasive breast carcinoma of no special type (eg, invasive lobular carcinoma, invasive ductal carcinoma), inflammatory breast cancer (IBC) and so on. Among them, invasive breast carcinoma of no special type is the most common type and IBC patients often show a poor prognosis. According to molecular type [estrogen receptor (ER), progesterone receptor (PR) and human epidermal growth factor receptor-2 (HER-2)], human breast cancer is divided into luminal A (ER+, PR+, HER-2−), luminal B (ER+, PR+, HER-2+), normal breast-like, HER-2 over-expressing, and basal-like breast cancer. Triple-negative breast cancer (TNBC) is a subtype of basal-like breast cancer that is characterized by the absence of expression of ER, PR and HER2. With high proliferative capacity and recurrence rate, poor differentiation with large tumor size and lack of recognized biomarker, TNBC is a clinical challenge...
for targeted therapy.\textsuperscript{15–17} Canine mammary tumor (CMT) is considered a suitable model for human breast cancer, owing to it showing a similar tumor microenvironment (TME), carcinogens and cancer risk factors.\textsuperscript{18,19} Cancer-associated fibroblasts (CAFs) play a key role in cancer initiation and progression.\textsuperscript{20} Although significant advances in surgery, chemotherapy and radiotherapy have greatly improved the prognosis of breast cancer patients,\textsuperscript{21} breast cancer still remains one of the most common causes of female death. Therefore, it is necessary to summarize the latest molecular mechanisms related to breast cancer progression.

Caveolae are 50–100 nm \textit{Ω}-shaped,\textsuperscript{22,23} cholesterol-enriched, rigid membrane microdomains that are composed of scaffold proteins named caveolins, including caveolin-1, caveolin-2 and caveolin-3 (Figure 1); caveolin-1 and caveolin-2 are expressed in all human tissues, while caveolin-3 is expressed in muscles.\textsuperscript{24–28} Caveolin-1 (Cav1) is a 21–22 kDa integral membrane protein and the coding gene of \textit{CAV1} is located in the D7S522 locus in the q31.1 region of human chromosome 7 and consists of three exons.\textsuperscript{29} Further, Cav1 can participate in various events including endocytosis, signal transduction, membrane trafficking, cholesterol homeostasis, lipid transport and storage, cell cycle, proliferation, apoptosis, cancer cell invasion, migration and metastasis.\textsuperscript{30–38} In normal mammary parenchymal cells’ carcinogenic process, Cav1 can act both as tumor suppressor and promoter depending on the subtypes and stages of cancers.\textsuperscript{39–41} In addition, recent studies have shown that caveola integrity is associated with cancer cell survival, apoptosis and migration and metastasis;\textsuperscript{42–45} so we consider Cav1 in caveolae may play a necessary role in the breast cancer development.

In order to define the interaction between Cav1 and breast cancer, in this review, we cover the state-of-the-art study, development and progress on Cav1 and breast cancer, altogether describing the role of Cav1 in breast cancer progression, including cell proliferation, apoptosis, autophagy, invasion, migration and breast cancer metastasis. Moreover, the application of Cav1 in breast cancer clinical treatment is also clarified, such as chemotherapeutics resistance, radiotherapy resistance and diagnosis, in the hope of promoting the clinical application of Cav1.

**Cav1 and breast cancer cell proliferation**

Cav1-induced changes in the expression and activation of ion channels and receptors on the cell membrane may play an important role in breast cancer cell proliferation. Cav1 can act as a tumor suppressor in MCF-7 cells, the downregulation of Cav1 can promote the proliferation by increasing membrane expression and function of large conductance Ca\textsuperscript{2+}-activated potassium (BKCa) channel whose encoding gene contributes to malignancy, thus accelerating the process of carcinogenesis.\textsuperscript{46} Contrarily, parenchymal Cav1 can also act as a tumor promoter by promoting EGFR binding to the kinase domain of caveolin-binding motif, thereby potentially activating EGFR-mediated mitosis initiation.\textsuperscript{47} HER2 overexpression and excessive HER2 signaling were observed in 25% of breast cancer patients with poor prognosis;\textsuperscript{48} so Alawin et al allowed \(\gamma\)-tocotrienol to accumulate within the caveolae microdomain, which lead to caveolae disruption, subsequent interference with HER2 dimerization in caveolae microdomain, phosphorylation (activation) and mitogenic signaling transduction in SKBR3 and BT474 human breast cancer cells.\textsuperscript{49}

Cav1 can decrease G0/G1 phase cell cycle arrest and increase the S phase cell number by activating the extracellular signal-regulated kinase (ERK) 1/2 pathway and increasing the expression of cell cycle-associated proteins (cyclin D1 and \(\beta\)-catenin) in BT474 cells.\textsuperscript{50} On the contrary, Cav1 acts as an antiproliferative factor in MDA-MB-231 and MCF-7 cells through promoting cell cycle arrest in the G2/M phase, which was accomplished by upregulation of p21, p27 and cyclin B1 and downregulation of cyclin D2, and this antiproliferative effect was enhanced with the cooperation of docetaxel (DTX).\textsuperscript{51} The completely opposite effect of Cav1 on cell proliferation may be due to the difference of used cell lines in two experiments, and more importantly, breast cancer cells were treated with DTX in Kang et al’s study.

The malignant features of cancer cells can not only affect tumor development but also the interaction between neoplastic cells and the TME can act as a significant factor in

![Figure 1 The structure of caveolae.](image)

**Notes:** Caveolae are 50–100 nm \textit{Ω}-shaped, cholesterol-enriched, rigid membrane microdomains that are composed of scaffold proteins named caveolins. The most important constituent protein is Caveolin-1.
the process of breast cancer progression, and Cav1 plays a multifunctional role in this process. High oxidative stress is usually observed in the stroma of human breast cancers and it can induce stromal catabolism, stromal Cav1 transportation from cancer-associated stroma to breast cancer cells is low and this leads to a proliferative effect. Bisphenol A (BPA) is commonly used as an analog of estrogen to mimic estrogenic effects. Xu et al found that under a hypoxic TME, BPA in MDA-MB-231 cells could trigger G-protein estrogen receptor competitive binding to Cav1, leading to the release of heat shock protein 90 to stabilize and activate hypoxia inducible factor-1 alpha, which upregulated the expression of vascular endothelial growth factor (VEGF), thus inducing proliferative effects. In addition to a hypoxic TME, the effect of CAFs is another factor which influences the occurrence and progression of breast cancers. Reduced expression levels of Cav1 mRNA and Cav1 in CAFs trigger the expression and secretion of stromal cell-derived factor-1, EGF and fibroblast-specific protein-1 (FSP-1), and all of them can accelerate breast cancer cell proliferation rate.

As mentioned above, we demonstrate that Cav1 can affect breast cancer cell proliferation rate by 1) influencing the expression and activation of ion channels and receptors on the cell membrane, such as BKCa channel, EGFR and HER2; 2) regulating cell cycle arrest and affecting mitosis process and 3) mediating the interaction between the TME (hypoxia conditions and CAFs) and breast cancer cells.

Cav1 and breast cancer cell autophagy and apoptosis

Apoptosis is a complex biological process with the formation of apoptotic bodies and morphological and biochemical changes in the nucleus, and both the intrinsic and extrinsic apoptotic pathways are typically inhibited in cancer cells through overexpression of antiapoptotic proteins and underexpression of proapoptotic proteins. Autophagy is a process known to degrade intracellular proteins and organelles by forming various membrane structures, including autophagosomes, lysosomes and autolysosomes. Novel types of selective autophagy have been identified, including mitophagy, pexophagy, lipophagy, ERphagy and nucleophagy, all of them facilitate the removal of damaged cellular compartments and recycle components, thereby preventing cells from apoptosis and increasing survivability.

Cav1 can regulate intrinsic and extrinsic apoptotic pathway proteins, thus affecting the process of breast cancer cell apoptosis. Owing to lipid rafts being enriched with cholesterol, methyl beta cyclodextrin (MβCD) as a cholesterol depleting agent can induce lipid raft disruption andmediate MDA-MB-231 and 468 cells apoptosis by down-regulating the mRNA and protein expression level of Cav1 and Wnt receptor LRp6, and they can synergistically affect expression of apoptosis-related protein, such as survivin, Bcl-2, Bax and caspase-3. On the contrary, with the DTX treatment, elevated mRNA and protein expression level of Cav1 in TNBC cells induces Bcl-2 phosphorylation (inactivation) and expression of p53, Bax and cleaved poly-ADP-ribose polymerase, thus exposing MCF-7 and MDA-MB-231 cells to the apoptotic process.

Cav1-induced autophagy alternation can influence cell apoptosis. An enhanced expression level of autophagy-related proteins (Bclin-1, light chain 3-II and Atg12/5) in BT474 cells is realized by 17β-estradiol (E2)-induced Cav1 upregulation, resulting in the formation of autophagosome and inhibition of apoptosis. Shi et al found that Cav1 deficiency and lipid raft disruption could elevate autophagy levels and inhibit apoptosis by promoting V-ATPase assembly, which could activate lysosomal function and autophagosome–lysosome fusion.

Chemotherapeutic drugs can regulate transcriptional level of CAV1, thus promoting apoptosis of breast cancer cells. Salis et al found that fluvastatin induced cytotoxic effects on MCF-7 cells through a reduction of the mRNA expression levels of CAV1 and serum and glucocorticoid-regulated kinase 1 (SGK1), conversely, they also found metformin-induced cytotoxic effect on MCF-7 cells was realized by an enhanced mRNA expression of CAV1 while a reduction of SGK1, and the different transcriptional regulation of CAV1 may be owing to the different chemotherapeutic drug treatments with MCF-7 cells.

Cav1 can affect the apoptotic process by regulating the expression and activation of downstream proteins. Reduced expression levels of Cav1 in CAFs lead to upregulation of tumor protein 53-induced glycolysis and apoptosis regulator (TIGAR) in the BT474 cells, which functions to limit ROS, thus preventing cells from ROS-induced apoptosis. Docosahexaenoic acid (DHA) can facilitate caveolae internalization by sensitizing caveolae marker Cav1 to lysosomal marker LAMP-1, thereby decreasing caveolae-associated onco-protein levels via proteasomal and lysosomal pathways and decreasing HSP90 function.

As mentioned above, we demonstrate that the interaction between Cav1 and breast cancer cell apoptosis can be summarized as follows: 1) Cav1 can regulate intrinsic and extrinsic apoptotic pathway proteins, such as Bcl-2, Bax and caspase-3; 2) Cav1-induced autophagy alternation can
influence cell apoptosis; 3) chemotherapeutic drugs can regulate transcriptional level of CAV1 promoting apoptosis; and 4) Cav1 can affect apoptosis process by regulating the expression and activation of downstream proteins, such as TIGAR, ROS and onco-proteins.

**Cav1 and breast cancer cell invasion and migration**

It is clear that epithelial to mesenchymal transition (EMT) plays a critical role in cancer progression and metastasis, and Cav1 is implicated in various aspects of EMT, thus driving breast cancer progression.\(^{71-73}\) The downregulation of epithelial markers (eg, E-cadherin and γ-catenin), upregulation of mesenchymal markers (eg, vimentin, fibronectin and N-cadherin) and transcription factors (eg, Snail and Slug) together with the acquisition of increased invasion, migration and stem-like properties are key features of the EMT program.\(^{74-76}\) Matrix metalloproteinases (MMPs) are major extracellular enzymes with the capacity of degrading and remodeling extracellular matrix (ECM) proteins and basement membranes, resulting in local invasion,\(^{77-79}\) thus promoting cancer initiation, progression, invasion, migration and metastasis.\(^{80}\)

During hyperglycemia-induced matrix-specific EMT, inhibition of fatty acid synthase/ER\(\alpha\) signaling leads to a dramatic upregulation of Cav1 mRNA and protein, thereby enhancing Slug mRNA levels and promoting invasion capacity in MCF-7 and T47D cells.\(^{31}\) Fucose-containing fraction of Ling-Zhi (FFLZ) inhibits the Cav-1/Smad7/Smurf2-dependent ubiquitin-mediated transforming growth factor-β receptor (TGFR) degradation and abolishes TGFR signaling pathways, thereby reducing the expression of EMT markers (eg, Snail and Slug) and suppressing 4T1 and MDA-MB-231 cells migration.\(^{82}\) In an in vitro study, Cav1 and EMT-related gene expression inhibition was observed in curcumin\(^{83}\) and pamidronate\(^{84}\)-treated MCF-10F cells.

Cav1 knockdown can inhibit BT474 cell invasion and migration capacities via downregulating the protein expression of MMP-2, MMP-9 and MMP-1.\(^{50}\) Antarctic krill DHA enhanced the interaction between CD95 (known as Fas) and Cav1, resulting in the downregulation of MMP-2 expression through the inhibition of FAK/SRC/P13K/AKT signaling pathway in MCF-7 cells.\(^{53,56}\) Cav1 and MMP-14 overexpression was observed in malignant and invasive CMT tissues.\(^{18}\)

Rho GTPases play a key role in the process of microtubule cytoskeleton or actin regulation and thus regulate cell adhesion and migration.\(^{87}\) Activation of Cav1 in IBC cells resulted in increasing invasive potential via Akt1 pathway, which phosphorylates RhoC GTPase.\(^{88}\) Yang et al found that whether upregulation or downregulation of ROS, the migration capacity of MCF-7 and MDA-MB-231 cells was obviously inhibited via reducing the interaction between Cav1 and DLC1,\(^{89}\) which belongs to the Rho GTPase-activating protein (GAP) family.\(^{90}\) Diaz et al reported that Cav1 can recruit p85α (a Rab5 GAP) and thus precluding p85α-mediated Rab5 inactivation, and activated Rab5 can increase Rac1 activity and enhance MDA-MB-231 cells migration and invasion.\(^{91}\)

Endocytic trafficking of integrins plays a significant role in cell adhesion and migration, which are related to cancer cell dissemination. Focal adhesion associated kinases (FAK)-induced phosphorylation of Cav1 on Tyr14 can internalize ligand-bound integrins to early endosomes; pro-metastatic protein NEDD9-dependent dephosphorylation of pTyr14-Cav1 is required for the transformation of early endosomes to late endosomes and this leads to individual MDA-MB-231 cell migration.\(^{92}\)

As mentioned above, we demonstrate that Cav1 can affect breast cancer cell invasion and migration by 1) influencing the expression level of EMT-associated markers and transcription factors; 2) affecting the expression level of MMP; 3) regulating the expression of Rho GTPases and 4) participating Cav1-dependent trafficking of integrins.

**Cav1 and breast cancer metastasis**

Proliferation, cell cycle arrest, cell transport, adherence, extravasation, motility, adhesion local invasion and migration are necessary preparation for breast cancer metastasis and the prognosis of metastatic breast cancer patients is still poor.\(^{93,94}\) Various steps are involved in the cancer metastasis process, including tumor cell detachment and escape, survival in the circulatory system and ultimately growth in distant organs.\(^{95,96}\) Once normal epithelial cells detach from the surrounding ECM, a form of programmed apoptosis termed anoikis will be triggered.\(^{97}\) To survive in the circulatory and lymphatic system, circulating tumor cells (CTCs) must acquire the ability to resist anoikis, thereby facilitating secondary tumor formation in distant sites.\(^{98,99}\) Some metastatic tumor cells are less sensitive or even resistant to anoikis and can survive without attachment to ECM.\(^{100}\)

Cav1 regulates breast cancer metastasis via participating in anoikis progression. Once MDA-MB-231 cells detach from the ECM and enter into a hemodynamic environment, expression of Cav1 mRNA and protein is enhanced by the fluid-induced low shear stress and Cav1 can endow cancer cells with anoikis resistance via inactivating caspase-8.\(^{101}\) Similarly, Cav1 endows anoikis resistance to MDA-MB-231
cells via activation of PI3K/AKT and MEK/ERK survival signaling pathways and ITGB1–FAK signaling. Increasing evidence suggests that increased Cav1 expression is associated with drug resistance, and Cav1 overexpression in breast cancer cells can mediate drug resistance through its role in the MDR1/P-glycoprotein pathway. 

Membrane type 4 matrix metalloproteinase (MT4-MMP) co-localizes with Cav1 at the cell surface, and Cav1 knockdown increases the sensitivity of breast cancer cells to chemotherapeutics, indicating a potential therapeutic target for breast cancer therapy.

Cav1 and chemotherapeutics and radiotherapy resistance

Drug resistance is considered one of the most important factors influencing the prognosis of cancer patients. Thirty percent of patients with early-stage breast cancer have developed metastatic disease with the majority of these being resistant to current chemotherapeutics. Cav1 is a potential target for preventing cancer radiation and drug resistance and improving clinical outcomes.

With the capacity of mediating chemically cytostatic drugs efflux, breast cancer resistance proteins (BCRP) play an important role in clinical breast cancer drug resistance. ATP-binding cassette subfamily G member 2 (ABCG2) is one of the BCRPs. An elevated Cav1 mRNA and protein expression level was observed in TNBC stem cells, altogether enhancing expression level of ABCG2 via downregulating the Cav1-related β-catenin proteosomal degradation pathway and upregulating intracellular β-catenin accumulation. Similarly, Herzog et al also found that knockdown of Cav1 decreased activity of ABCG2 and sensitized drug resistant breast cancer cells to chemotherapeutics.

Trastuzumab emtansine (T-DM1) is an antibody drug conjugate (ADC) that has been approved by the US Food and Drug Administration to treat HER-2-positive metastatic breast cancer. The trastuzumab in T-DM1 can bind to HER-2 receptors, followed by internalization of T-DM1 into cells and release of emtansine, resulting in cell toxicity. Recent studies have demonstrated that Cav1 can co-localize with trastuzumab to mediate T-DM1 internalization and enhance drug toxicity. The elevated Cav1 expression could mediate endocytosis and promote the internalization of T-DM1 into HER2-positive cancer cells. Chung et al reported that Cav1 in BT-474 cells enhanced drug sensitivity by promoting T-DM1 internalization. It is worth mentioning that mRNA profiling reveals that low Cav1 expression seems to sensitize BT474 cells to T-DM1. And, in addition to internalization, Cav1 can mediate N87-TM cells’ resistance to T-DM1 via altering endocytic ADC to the lysosome and degrading T-DM1.

Cav1 overexpression in MCF-7 and MDA-MB-231 cell lines abolished the chemosensitizing effects by inhibiting eNOS/NO/ONOO− pathway and oxidant damage. In ER(+) breast cancer cells, the MAPK pathway induced by Src phosphorylation can further phosphorylate Cav1, which activates the ER pathway and confers acquired resistance to lapatinib. Radiation-induced Cav1 elevation promotes EGFR nuclear translocation and activates DNA-dependent protein kinase, following DNA repair and formation of radiation resistance.

As mentioned above, we demonstrate that Cav1 can affect breast cancer cell chemotherapeutics and radiotherapy resistance by 1) affecting the expression and activity of BCRP (eg, ABCG2); 2) influencing Cav-1-mediated T-DM1 internalization; 3) regulating eNOS/NO/ONOO− pathway and ER pathway and 4) promoting repair of radiation-induced DNA damage.

Cav1 and cancer stem cell

Tumor initiation is closely related to resistance to chemotherapeutics and radiotherapy resistance, and various approaches have been hypothesized to solve this issue. Over the past decades, few researchers have addressed the issue of reversing drug resistance. Cancer stem cell (CSC) is increasingly set to become a vital factor in resistance to chemotherapeutics or radiotherapy, and it has been considered as a potential pathway for tumor recurrence in a variety of cancers, which significantly influences the clinical outcomes of patients. This means, if a therapeutic agent fails to
Cav1 and breast cancer prognosis

Cav1 is emerging as a potential therapeutic biomarker for breast cancer treatments.40 Epithelium Cav1 and stroma Cav1 may be useful as prognostic indicators for patient treatments and assist the selection of personalized therapy.141 Both the epithelial and stromal Cav1 have been detected in breast cancer cells, and can be used to forecast the prognosis. Breast cancer patients with negative Cav1 expression in CAFs often show a poor outcome and low survival rate.142,143 Absence of Cav1 expression in CAFs allows patients with lymph node metastasis and poor prognosis.7 Lack of stromal Cav1 expression is associated with a poor prognosis and worsen overall survival.144–146 High expression level of Cav1 in invasive breast cancer cells indicates that epithelial Cav1 expression is proportional to tumor aggressiveness and poor prognosis.140,147 Besides, Qian et al reported that tumor (++)/stromal (−) Cav1 expression was closely associated with poor prognostic outcomes in primary human breast cancer patients.148

In addition to the breast cancer cells with low stromal Cav1 expression (38.56%), Liang et al also found overexpression of cytoplasmic EGFR (53.92%) and Cav1 (44.12%), and suggested the combined stromal Cav-1/EGFR expression as an advanced prognostic marker.47 It is also reported that lack of Cav1 and overexpression of monocarboxylate transporter 4 (MCT-4) in stroma show a prognostic significance to breast cancer patients.149

As mentioned above, we demonstrate that stromal Cav1 expression may be a potential prognostic indicator for breast cancer patients and loss of stromal Cav1 expression often shows a poor clinical outcome. What is more, high expression levels of epithelial Cav1, cytoplasmic EGFR and stromal MCT-4 may be secondary prognostic indicators (Figure 2).

Conclusion and future perspective

Nowadays, breast cancer is one of the most common cancer diseases and causes of death among female population worldwide. Human breast cancer shows different pathological types, including non-invasive breast cancer, invasive breast carcinoma of special type, invasive breast carcinoma of no special type, IBC and so on. Different pathological types of breast cancer show different epidemiological characteristics and prognosis: invasive lobular carcinoma is the second most common subtype of mammary cancer to invasive ductal carcinoma,150 non-invasive breast cancer is a type of breast cancer with a better prognosis, while IBC patients often show a poor prognosis. According to whether the cancer cell plasma membrane expresses ER, PR and HER2, mammary cancer can be divided into luminal A, luminal B, normal breast-like, HER-2 over-expressing and basal-like breast cancer. TNBC is a subtype of basal-like breast cancer with poor prognosis. Cav1 is the main component of caveolae, and it participates in various biological events. It has been reported that genetic changes of Cav1 might modify the risk for breast cancer,151 and Cav1 acts both as a tumor suppressor as well as an oncogene, and plays a key role in breast cancer tumorigenesis.152 In addition to breast cancer carcinogenic process, Cav1 is also associated with lung cancer,153,154 colorectal cancer,155 gastric cancer,156,157 cervical cancer,158 hepatocellular carcinoma,159 pancreatic cancer,160 bladder cancer,161 pulmonary hypertension,162–164 virus infection,165,166 cardiovascular disease,167,168 diabetes mellitus,169 nanomedicines endocytosis170...
and lipodystrophy. \cite{171} Besides, it has been reported that caveolin-2 (Cav2) can also mediate the initiation and development of breast cancer. \cite{26}

We discuss the role of Cav1 in ER-positive or -negative breast cancer, and notice several contrary results. With regard to cancer cell apoptosis, Chintala et al noted that downregulation of tumor promoter Cav1 by MβCD contributed to MDA-MB-231 (ER−) apoptosis. \cite{65} Their results were contradicted by the experiments of Kang et al, who showed that elevated expression level of Cav1 exposed TNBC cells (MDA-MB-231 cells) to the apoptotic process that suggested Cav1’s role as a tumor suppressor. \cite{51} With regard to chemotherapy and radiotherapy resistance, Cav1, considered as a tumor suppressor, was phosphorylated by MAPK pathway and conferred acquired resistance to lapatinib in ER(+) breast cancer cells. \cite{125} However, interestingly, this is contrary to the results of a study conducted by Zou et al in TNBC cells that demonstrated Cav1 as a tumor promoter via promoting DNA repair and formation of radiation resistance. \cite{126} From the aspect of effect of Cav1 in these cases, conclusions seem totally contrary. Among the plausible explanations for these findings are different cell lines and signaling pathways, indicating whether ER expressed in different types of BC may result in diverse interaction with Cav1 and signaling pathways.

In the current review, we found that Cav1 acts both as a tumor suppressor as well as a promoter, and plays a key role in breast cancer tumorigenesis (Figure 3). We also summarized the role of Cav1 in the development of breast cancer, in the hope of providing a basis for molecular targeted therapy of breast cancer (Tables 1 and 2). We have demonstrated the interaction between Cav1 and human breast cancer.

1. Cav1 can affect breast cancer cell proliferation rate by 1) influencing the expression and activation of ion channels and receptors on the cell membrane, such as BKCa channel, EGFR and HER2; 2) regulating cell cycle arrest and affecting mitosis process; and 3) mediating the interaction between the TME (hypoxia conditions and CAFs) and breast cancer cells.

2. Cav1 can affect breast cancer cell apoptosis by 1) regulating intrinsic and extrinsic apoptotic pathway proteins, such as Bcl-2, Bax and caspase-3; 2) Cav1-induced autophagy alternation can influence cell apoptosis; 3) chemotherapy drugs can regulate transcriptional level of CAV1 and promote apoptosis; and 4) regulating the expression and activation of apoptosis-related molecules, such as TIGAR, ROS and onco-proteins.

3. Cav1 can affect breast cancer cell invasion and migration by 1) influencing the expression level of EMT-associated markers and transcription factors; 2) affecting the expression level of MMPs; 3) regulating the expression of Rho GTPases and 4) participating Cav1-dependent trafficking of integrins.

4. Cav1 can affect breast cancer metastasis by 1) participating in anoikis progression; 2) regulating the expression and transport of metastasis-associated proteins, such as MT4-MMP, MMP9 and TLR4 and 3) the expression levels and methylation of Cav1 are associated with metastatic breast cancer.

**Figure 2** Cav1 and breast cancer prognosis.

*Notes:* CAFs and epithelium Cav1 expression may be primary prognostic indicators for breast cancer patients. Loss of CAFs Cav1 expression and high expression levels of epithelium Cav1 often show a poor clinical outcome. Moreover, cytoplasmic EGFR and stromal MCT-4 may be secondary prognostic indicators.

*Abbreviations:* CAFs, cancer-associated fibroblasts; Cav1, caveolin-1; MCT-4, monocarboxylate transporter 4.
5. Cav1 can affect breast cancer cell chemotherapeutics and radiotherapy resistance by 1) affecting the expression and activity of BCRP (eg, ABCG2); 2) influencing Cav-1-mediated T-DM1 internalization; 3) regulating eNOS/NO/ONOO⁻ pathway and ER pathway and 4) promoting repair of radiation-induced DNA damage.

6. Stromal Cav1 expression may be a potential prognostic indicator for breast cancer patients and loss of stromal Cav1 expression often show a poor clinical outcome. What is more, high expression levels of epithelial Cav1, cytoplasmic EGFR and stromal MCT-4 may be secondary prognostic indicators.

The molecular pathways that Cav1 impacts and breast cancer are interrelated. EGFR and HER2 are receptors on the breast cancer cell membrane, and Cav1 promotes breast cancer cell proliferation via EGFR or HER2-induced mitogenic signaling pathway. Besides, the regulation of cell cycle-associated proteins (eg, cyclin B1, cyclin D1, cyclin D2 and β-catenin) is a significant way that Cav1 affects the cell proliferation rate. The activation of ERK pathway not only promotes the proliferation but also endows anoikis resistance to cancer cells, ultimately promoting the progression of breast cancer. High oxidative stress promotes cell proliferation by regulating oxidative damage. VEGF is another targeted molecule in Cav1-mediated breast cancer tumorigenesis. Activation of Cav1 upregulates VEGF and promotes cell proliferation, contrarily, Cav1 loss enhances VEGF-A/VEGFR1 activity and facilitates angiogenesis and metastatic growth. The regulation of intrinsic and extrinsic apoptotic pathway-related molecules (eg, survivin, Bel-2, Bax caspase-8 and caspase-3) is an important process in Cav1-induced apoptosis, and inactivation of caspase-8 can inhibit apoptosis and endow anoikis resistance to cancer cell. MMPs (eg, MMP-1, MMP-2, MMP-9, MMP-14 and MT4-MMP) are key proteins in the EMT process that promotes breast cancer invasion, migration and metastasis. Cav1-induced MMP-2 upregulation promotes BT474 cells’ invasion and migration, while Cav1 can also downregulate the expression of MMP-2 in MCF-7 via inhibiting PI3K/AKT signaling pathway ultimately suppressing invasion and migration. Cav1-mediated PI3K/AKT signaling pathway activation can promote anoikis resistance. To sum up, Cav1-mediated breast cancer progression-related molecular pathways are correlational, it not only shows the same or opposite effect in the same stage but also in different stages.

Caveolae are cholesterol-enriched rigid membrane microdomains that are composed of caveolins, including Cav1, Cav2 and Cav3. Therefore, the treatment of breast cancer may be achieved by targeting Cav1. First, the use of...
targeted drugs (eg, γ-tocotrienol and MβCD) to accumulate within the caveolae microdomain, thereby disrupting the structure of caveolae and blocking the Cav1-mediated signaling pathway, may be a means of breast cancer-targeted therapy.49,65,67 Second, targeted drug-induced regulation of Cav1 expression level may be another targeted treatment.51 Besides, targeted drugs (eg, FFLZ and antarctic krill DHA) regulate the activation of Cav1 and Cav1-mediated

<table>
<thead>
<tr>
<th>Progress stages</th>
<th>Cell lines</th>
<th>Signaling cascades</th>
<th>Promoter/suppressor</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proliferation, invasion</td>
<td>MCF-7</td>
<td>Cav1↑ → BKCa↓</td>
<td>Suppressor</td>
<td>46</td>
</tr>
<tr>
<td>Proliferation</td>
<td>SKBR3 BT-474</td>
<td>γ-tocotrienol → caveolae disruption → HER2 signaling↓</td>
<td>Promoter</td>
<td>49</td>
</tr>
<tr>
<td>Proliferation, invasion, migration</td>
<td>BT-474</td>
<td>Cav1↑ → cell cycle arrest↓</td>
<td>Promoter</td>
<td>50</td>
</tr>
<tr>
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<td>MDA-MB-231 MCF-7</td>
<td>Cav1↑ → cell cycle arrest↑</td>
<td>Suppressor</td>
<td>51</td>
</tr>
<tr>
<td>Proliferation</td>
<td>MDA-MB-231</td>
<td>BPA → Cav1-GPER↑ → HSP90, HIF-1α, VEGF↑</td>
<td>Promoter</td>
<td>52, 58</td>
</tr>
<tr>
<td>Proliferation</td>
<td>BT-474</td>
<td>CAFs Cav1↑ → SDF-1, EGF, FSP-1↑</td>
<td>Suppressor</td>
<td>59</td>
</tr>
<tr>
<td>Apoptosis</td>
<td>MDA-MB-231</td>
<td>MjICD → Cav1↓ → apoptotic pathways↑</td>
<td>Promoter</td>
<td>65</td>
</tr>
<tr>
<td>Apoptosis</td>
<td>MDA-MB-231 MCF-7</td>
<td>Cav1↑ → apoptotic pathways↑</td>
<td>Suppressor</td>
<td>51</td>
</tr>
<tr>
<td>Autophagy</td>
<td>BT-474</td>
<td>E2 → Cav1↑ → autophagosome↑</td>
<td>Promoter</td>
<td>66</td>
</tr>
<tr>
<td>Autophagy</td>
<td>MCF-7</td>
<td>Cav1↓ → V-ATPase assembly↑ → autophagosome-lysosome fusion↑</td>
<td>Suppressor</td>
<td>67</td>
</tr>
<tr>
<td>Apoptosis</td>
<td>MCF-7</td>
<td>Fluvasatin → GAVI mRNA expression↓</td>
<td>Promoter</td>
<td>68</td>
</tr>
<tr>
<td>Apoptosis</td>
<td>MCF-7</td>
<td>Metformin → GAVI mRNA expression↑</td>
<td>Promoter</td>
<td>69</td>
</tr>
<tr>
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<td>MDA-MB-231 SK-BR-3</td>
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<td>Suppressor</td>
<td>70</td>
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<td>Invasion, migration</td>
<td>MCF-7</td>
<td>Cav1↑ → Slug↑ → EMT↑</td>
<td>Promoter</td>
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<td>Invasion, migration</td>
<td>MDA-MB-231 T47D</td>
<td>FFLZ → Cav-1Smad7/Smurf2↑ → TGFR signaling↑ → EMT↓</td>
<td>Promoter</td>
<td>82</td>
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<tr>
<td>Invasion, migration</td>
<td>MCF-10F</td>
<td>Curcumin, pamidronate → Cav1↓ → EMT↓</td>
<td>Promoter</td>
<td>83, 84</td>
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<td>Invasion</td>
<td>MCF-7</td>
<td>AnticarDkD DHA → Cav1-Fas↑ → MMP-2↓</td>
<td>Suppressor</td>
<td>86</td>
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<td>Migration</td>
<td>MDA-MB-231 MCF-7</td>
<td>ROS → Cav1-GAP↓</td>
<td>Promoter</td>
<td>90</td>
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<td>Invasion, migration</td>
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<td>Promoter</td>
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<td>Anoikis</td>
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<td>LSS → Cav1↑ → caspase-8↓ → anoikis↓</td>
<td>Promoter</td>
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<td>Cav1↑ → ITGβ1-FAK↑ → anoikis↓</td>
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<td>Metastasis</td>
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<td>Cav1↑ → MT4-MMP recycling↑</td>
<td>Promoter</td>
<td>104</td>
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<tr>
<td>Metastasis</td>
<td>E0771</td>
<td>Cav1↑ → VEGF-A/VEGFR↑ → MMP9, CSF1↑</td>
<td>Suppressor</td>
<td>105</td>
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<tr>
<td>Metastasis</td>
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<td>MIF → Cav1 phosphorylation↑ → HMGB1↑ → TLR4/ NF-kappa B↑</td>
<td>Promoter</td>
<td>106</td>
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<td>Drug resistance</td>
<td>MCF-7 MDA-MB-231</td>
<td>Cav1↑ → ABCG2↑ → drug resistance↑</td>
<td>Promoter</td>
<td>114</td>
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<td>Drug resistance</td>
<td>BT-474</td>
<td>Cav1↑ → T-DM1 internalization↑</td>
<td>Promoter</td>
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<td>Drug resistance</td>
<td>MCF-7</td>
<td>Cav1↑ → eNOS/NO/ONOO↓</td>
<td>Promoter</td>
<td>124</td>
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<tr>
<td>Radiation resistance</td>
<td>BT474 SKBR3 MDA-MB-231</td>
<td>Cav1↑ → EGF nuclear translocation↑ → DNA repair↑</td>
<td>Promoter</td>
<td>126</td>
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</table>

Abbreviations: ABCG2, ATP-binding cassette subfamily G member 2; BKCa, large conductance Ca2+-activated potassium; BPA, Bisphenol A; CAFs, cancer-associated fibroblasts; Cav1, caveolin-1; CSF1, colony-stimulating factor 1; DHA, docosahexaenoic acid; EMT, epithelial to mesenchymal transition; FAK, focal adhesion associated kinases; FFLZ, fucose-containing fraction of Ling-Zhi; FSP-1, fibroblast-specific protein-1; GAP, GTPase-activating protein; GPER, G-protein estrogen receptor; HER2, human epidermal growth factor receptor-2; HIF-1α, hypoxia inducible factor-1 alpha; HSP90, heat shock protein 90; LSS, fluid-induced low shear stress; MIF, migration inhibitory factor; MMP, matrix metalloproteinase; MT4-MMP, membrane type 4 matrix metalloproteinase; MjICD, methyl beta cyclodextrin; SDF-1, stromal cell-derived factor-1; T-DM1, trastuzumab emtansine; TGFR, transforming growth factor-β receptor; VEGF, vascular endothelial growth factor.
signaling cascades, ultimately inhibiting the progression of breast cancer. More importantly, targeted drugs (eg, DHA and T-DM1) can facilitate caveolae-mediated chemotherapy drug internalization by sensitizing caveolae marker Cav1, thus preventing drug resistance and improving therapeutic effect.  

Although we have summarized the relationship between Cav1 and a certain tumor progression process in this review, the effect of Cav1 on the development of breast cancer is continuous and multi-process (Tables 1 and 2). Apoptosis and cell proliferation are mutually restricted; autophagy can promote cell renewal and inhibit apoptosis and invasion and migration are necessary preparations for distant metastasis. It can be seen that the occurrence and tumorigenesis of breast cancer is a continuous process, and the influence of Cav1 is multi-stage and continuous. Above all, we believe the summary of the interaction between Cav1 and breast cancer can be a basis for further research and promote CAV1 gene as a potential target to diagnose and treat aggressive breast cancer.

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References


