



## Anti-tumour Treatment

## The role of autophagy in resistance to targeted therapies

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## ABSTRACT

Autophagy is a self-degradative cellular process, involved in stress response such as starvation, hypoxia, and oxidative stress. This mechanism balances macro-molecule recycling to regulate cell homeostasis. In cancer, autophagy play a role in the development and progression, while several studies describe it as one of the key processes in drug resistance. In the last years, in addition to standard anti-cancer treatments such as chemotherapies and irradiation, targeted therapy became one of the most adopted strategies in clinical practices, mainly due to high specificity and reduced side effects. However, similar to standard treatments, drug resistance is the main challenge in most patients. Here, we summarize recent studies that investigated the role of autophagy in drug resistance after targeted therapy in different types of cancers. We highlight positive results and limitations of pre-clinical and clinical studies in which autophagy inhibitors are used in combination with targeted therapies.

## Introduction

*Targeted therapies for cancer*

Cancer is a multifactorial disease and one of the leading causes of death worldwide. Surgery, chemotherapy, and irradiation are the mainstream therapeutic approaches. Chemotherapeutic drugs act on rapidly dividing cells, but the main limitations are poor specificity and adverse effects. In the last years, a new generation of therapies have been developed to target cancer cells more specifically. Like conventional chemotherapy, targeted cancer therapies are based on compounds that inhibit cancer growth and metastasis [1]. However, they target specific cancer-associated pathways, reducing their impact on normal cells [2].

Targeted cancer therapies can be divided into 3 main groups: 1) monoclonal antibodies (mAbs), 2) small molecule inhibitors and 3) immunotoxins. Many of these approaches are already in different phases of pre-clinical and clinical trials.

According to the mechanism of action, MAb can be divided into

two classes: those that act independently of immune effector mechanisms, such as by induction of death signals mediated by cross-linking of surface receptor on the target cancer cell, or blocking an activation signal that is necessary for cancer cell growth; and those that require immune effector participation such as by antibody-dependent cellular cytotoxicity, complement mediated cytotoxicity and the ability of mAbs to alter the cytokine milieu or enhance development of an active anti-tumor immune response [3]. They are highly specific but can only interact with extracellular proteins as they cannot cross the plasma membrane. Over the past decade, multiple mAbs have gained approval by the U.S. Food and Drug Administration (FDA) to treat a wide range of cancers. Also, there are numerous pre-clinical and clinical trials involving mAbs for almost every type of cancer [1].

Small molecule inhibitors act by inhibiting proteins and blocking the activation of pathways that are dysregulated in cancer.

Tyrosine kinase (TK) inhibitors (TKIs) competitively bind to the active or inactive ATP binding site of a TK and are used to target proteins that are either downregulated or upregulated during cancer progression. When these molecules bind to their specific target, they block

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the tyrosine kinase domain and prevent the activation of downstream pathways. These drugs can be also used in conjunction with standard chemotherapy to improve therapeutic efficacy. To date inhibitors for over 20 different kinases have been developed and are in clinical trials [2]. Immunotoxins are basically modified mAbs or growth factors which have been conjugated to a toxin either by chemical bond or generated by recombinant DNA technology. The rationale is to deliver the toxin to a target expressed specifically by cancer cells.

Most of the pathways/targets of targeted therapy are also expressed by normal cells, thus targeted therapies are not free of adverse effects which limit their use. Most commonly reported adverse reactions are cutaneous rash, liver problem with hepatic enzyme elevation, elevated blood pressure, coagulation defects up to rare gastrointestinal perforation. However, some mild side effects are associated with better outcome [4,5].

However, the main limitation of targeted therapy is the development of drug resistance [6]. Molecular characterization of resistant cell lines has revealed a diverse range of mechanisms, both genetic and non-genetic. Genetic mechanisms include mutation of the target, e.g. functional hyperactivation and mutation at the site of drug binding. Non-genetic mechanisms of resistance include oncogene switching, where a different protein substitutes the drug target, e.g. a growth factor receptor or kinase, or compensatory activation of other signaling pathways [7]. Also, autophagy has been shown to play an important role in resistance to targeted therapy in many different cancer types.

### Autophagy

Autophagy is one of the most studied cellular processes through which intracellular components are delivered to lysosomes or other vacuoles for degradation [8]. Substrates of autophagy include aggregated proteins and damaged or excess organelles, e.g. mitochondria. The degradation products are recycled, which helps the cell to survive under different stress conditions (starvation and oxidative stress, etc.) [9]. Autophagy can be broadly classified into 3 sub-types: macroautophagy, microautophagy, and chaperone-mediated autophagy [10]. This review focuses on macroautophagy, which henceforth will be referred to as autophagy. Autophagy is characterized by the formation of autophagosomes: an isolation membrane (phagophore) encloses cytoplasmic material or organelles forming the autophagosome, which then fuses with lysosomes.

Autophagosome formation is driven by autophagy-related proteins (ATGs), which form the autophagy activating kinase (ULK) complex, and regulatory proteins such as AMP-activated protein kinase (AMPK), mammalian target of rapamycin complex 1 (mTORC1), vacuolar protein sorting 34 (VPS34), p150, Beclin 1, B cell lymphoma 2 (BCL-2), and others [11]. It can be divided into four steps:

- 1) Initiation: Proteins needed to initiate the membrane formation are recruited [12].
- 2) Nucleation: Nucleation leads to the formation of the autophagosome membrane from the membrane source [13].
- 3) Expansion: This phase occurs until the complete formation of the autophagosome. The ATG12-ATG5-ATG16L1 complex mediates the lipidation of microtubule-associated protein 1A/1B-light chain 3 (LC3), which recruits the autophagy targets [14].
- 4) Degradation: Autophagosome-lysosome fusion is mediated by LAMP-2 and the small GTPase Rab7 [15].

In cancer, autophagy plays a crucial role in several processes including tumorigenesis, drug resistance, metastasis, microenvironment interactions [16]. Some studies have demonstrated that autophagy counteracts tumorigenesis, and mice deficient for various effectors of autophagy show an increase in spontaneous tumors [17,18]. Prolonged autophagy can also result in so-called “autophagic cell death” or “type II programmed cell death” [19,20]. On the other hand, autophagy is

known to counteract different types of cellular stress (e.g. oxidative and endoplasmic reticulum stress) as induced by chemotherapy, radiotherapy and other types of cancer treatments [21–24]. Moreover, autophagy is involved in the recycling of some receptors resulting in reduced target therapy efficacy, thus and autophagy-deficient cells are more sensitive to target therapies [25].

Because of these biological effects, several autophagy inhibitors are being used in combination with different cancer treatments, including targeted therapies, to improve cytotoxic effects or revert drug resistance.

The most important autophagy inhibitors are:

Chloroquine (CQ) is widely known as a last stage inhibitor of autophagy as it interrupts the autophagosome-lysosome fusion step. CQ and its derivative hydroxychloroquine (HCQ) are the only FDA-approved drugs currently used in clinical trials, often combined with standard treatments [25].

Bafilomycin A1 (BafA1) also blocks the autophagosome-lysosome fusion by inhibiting V-ATPase, which prevents lysosome acidification [26].

3-Methyladenine (3-MA) blocks autophagy at an early stage, inhibiting class III phosphatidylinositol 3-kinase (PI3K). It is not considered a specific autophagy inhibitor, because it can also inhibit class I PI3Ks. Indeed, in some contexts, it can promote autophagy [27].

Specific and potent autophagy inhibitor-1 (Spautin-1) is an inhibitor of USP10 and USP13, that promotes the degradation of the PIK3C3/VSP34-Beclin 1 complex, thereby inhibiting autophagy [28].

Lys 05 is a CQ derivative that inhibits autophagy by accumulating in the lysosome [29].

### Breast cancer

#### Endocrine therapy

Hormone receptor-positive breast cancer (BC) is the most common type of BC with approximately 70% of tumors expressing hormone receptors (estrogen receptor (ER) or progesterone receptor) [30]. The majority of these patients receive endocrine therapy such as selective estrogen receptor modulators (SERMs), most commonly tamoxifen (TAM); aromatase inhibitors (AIs) such as exemestane and letrozole, and selective ER degraders such as fulvestrant [31]. In the clinic, the efficacy of these treatments is often limited by intrinsic or acquired resistance [32,33] and several studies have shown that the aforementioned drugs induce autophagy, which is associated with resistance [30].

Initially, autophagy was interpreted as a tumor-suppressive mechanism as, non-viable ER + MCF-7 cells showed increased numbers of autophagosomes after 4-hydroxy-tamoxifen (4-OHT) treatment [34]. Samaddar et al. suggested that autophagy was activated as a survival mechanism following 4-OHT treatment but failed to rescue the cells [35]. Both Samaddar et al. and Qadir et al. showed that TAM/4-OHT combined with autophagy inhibition (3-MA, bafilomycin A1 or siRNAs targeting Beclin 1, ATG5 and ATG7) restored the sensitivity to TAM/4-OHT in resistant MCF-7 cells [32,35]. Accordingly, overexpression of Beclin 1 induced resistance to SERMs 4-OHT and raloxifene [36]. Also, TAM-resistant and both TAM- and fulvestrant-resistant cells could be re-sensitized by the autophagy inhibitor CQ [37]. Additionally, resistance to the AI exemestane could be reverted to some extent by 3-MA and Spautin-1 [38,39].

In this context, different players were identified to regulate autophagy and anti-estrogen resistance (Table 1). Prolylcarboxypeptidase, glucose-regulated protein 78 and the long non-coding RNA H19 mediated 4-OHT resistance by up-regulating autophagy [40–42] whereas microRNA (miR)-214 increased the TAM and fulvestrant sensitivity in antiestrogen-resistant MCF-7 cells by inhibiting autophagy [43].

**Table 1**  
Summary of targeted therapies in which autophagy is involved in resistance.

| DRUG                | CLASS                 | TARGET                       | CANCER SUBTYPE AND STAGE OF TREATMENT  | EXPERIMENTAL MODEL   | AUTOPHAGY MECHANISM/EFFECT   | REF                     |
|---------------------|-----------------------|------------------------------|--|--|--|-------------------------|
| <b>LUNG</b>         |                       |                              |  |  |  |                         |
| Bevacizumab         | TKI                   | VEGF 1/2                     | *First-line therapy of unresectable, relapsed and/or metastatic NSCLC patients (also EGFR mutated) | TCGA data set analysis of LCs vs healthy patients<br>LUAD-CLs A549, H1299, H1688, H446<br>NSCLC-CLs HCC827 <sup>19del</sup> , HCC4006 <sup>19del</sup> , H358 <sup>wt</sup> , and H1975 <sup>L858R/7790M</sup> | The cytotoxic effect of Bevacizumab is improved by the UPSis Bortezomib/ MG132 induction of autophagy which culminates in the AGR2 degradation   | [134]                   |
| Erlotinib           | TKI                   | EGFR                         | *First-line therapy of advanced and/or metastatic NSCLC patients EGFR mutated                      | LUAD-CLs A549, NCI-H1299, NCI-H292, NCI-H1650 and SK-MES-1<br>Clinical phase I study on advanced NSCLC patients previously responded to EGFR inhibitor   | Addition of autophagy inhibitors enhances the erlotinib sensitivity to the cells<br>The EGFR inhibition of erlotinib induces impairment in PI3K/Akt/mTOR/p70S6K pathway activation which directly regulates autophagy flux<br>The administration of CQ and HCQ in combination with erlotinib is safe and well-tolerated. No robust clinical effect has been reported, except for an EGFR-mutant patient. | [106]<br>[107]<br>[108] |
| Afatinib            | TKI                   | EGFR ErbB2-3-4               | *Adult NSCLC patients locally advanced and/or metastatic EGFR mutated                              | LUAD-CLs H1975 <sup>L858R/7790M</sup> , and H1650 <sup>del19</sup><br>LC mouse models  | Akt/mTOR and Erk pathways regulate the afatinib-induced autophagy, leading to inhibition of Caspase-3 partially mediated apoptosis in H1975 and H1650  | [109]                   |
| Crizotinib          | ALKI                  | ALK<br>HGFR<br>c-Met<br>ROS1 | *First/second-line therapy for NSCLC patients ALK and/or ROS1 mutated                              | LUAD-CLs A549, H1299 H3122, and H3122CR-1<br>LC mouse models   | The Crizotinib resistant H3122 CL showed a different regulation of PI3K/Akt/mTOR, strictly correlated to the autophagy activation  | [115]                   |
| Vismodegib          | SHHI                  | SMO (smoothed)               | **Phase II clinical trial in patients with extensive-stage SCLC                                    | hLUAD-CLs A549 and NCI-H1975<br>LUAD xenograft mouse model   | Vismodegib resistance is promoted by autophagy that inhibits apoptosis by ROS elimination and GLI2 pathway up-regulation   | [135]                   |
| Trametinib          | MEKI                  | MEK1/2                       | *Adult NSCLC advanced patients BRAF V600 mutated   | KRAS <sup>G12D</sup> /TP53 <sup>Null</sup> mouse lung derived SC196 & SC274<br>Murine LC-CL SC274 <sup>KRASG12D/TP53Nu</sup>   | The MEK1/2 inhibition with Trametinib increased autophagy-mediated resistance to the drug, reverted by the use of CQ.  | [111]                   |
| <b>BREAST</b>       |                       |                              |  |  |  |                         |
| Tamoxifen (TAM)     | SERM                  | ER                           | *Postmenopausal patients with advanced HR + BC   | MCF-7 and T-47D ER + BC cell lines   | autophagy inhibition sensitized TAM/4-OHT-resistant cells to TAM/4-OHT   | [35]                    |
|                     |                       |                              |  | MCF-7 ER + BC cell line  | 4-OHT resistant in BC cells overexpressed PRCP which mediated resistance by up-regulating autophagy.<br>Inhibition of PRCP blocked development of 4-OHT resistance and restored 4-OHT sensitivity in resistant cells.)   | [41]                    |
|                     |                       |                              |  | MCF-7 (sensitive and TAM-resistant) ER + cell lines<br>MCF-7-TAMR-Tet-shH19 xenograft mouse model  | lncRNA H19 induced tamoxifen resistance in breast cancer by activating autophagy via the H19/SAHH/ DNMT3B axis.  | [41]                    |
| Raloxifene (4-OHT)  | SERM                  | ER                           | **Study of Tamoxifen and Raloxifene (STAR) in BC in postmenopausal women.                          | BC patient- derived tissues<br>MCF-7 and Beclin 1-overexpressing MCF-7   | Beclin-1 overexpression in BC cells, induced anti-estrogen resistance by sequestering ERα  | [37]                    |
| Fulvestrant (4-OHT) | Selective ER degrader | ER                           | *Postmenopausal advanced HR + BC patients  | MCF-7 (sensitive and TAM-resistant), LCC9 and ZR-75-1 ER + BC cell lines<br>MCF-7 and LCC9 xenograft mouse model   | CQ increased anti-estrogen responsiveness of TAM- and/or Fulvestrant- in resistant cell lines and TAM + CQ treatment sensitized TAM-resistant xenografts   | [37]                    |
|                     |                       |                              |  | MCF-7, (sensitive and TAM-resistant), MCF-7/LCC1 and MCF-7/LIC9 ER + BC cell lines<br>LCC1 and LCC9 xenograft mouse model<br>DMBA-induced BC rat model   | Inhibition of GRP78 restored anti-estrogen sensitivity through the activation of TSC2/AMPK signaling leading to autophagy inhibition. Concurrent Beclin 1 and GRP78 knockdown synergistically reduced proliferation under Fulvestrant treatment  | [40]                    |
| Exemestane          | AI                    | Aromatase                    | **Phase II clinical trial in advanced BC   |  |  |                         |

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Table 1 (continued)

| DRUG   | CLASS            | TARGET            | CANCER SUBTYPE AND STAGE OF TREATMENT   | EXPERIMENTAL MODEL  | AUTOPHAGY MECHANISM/EFFECT   | REF                                      |
|--|------------------|-------------------|---|---|--|--|
| Palbociclib  | CDK4/6 inhibitor | CDK4/6            | Locally advanced/metastatic HR +, HER2 negative BC  | aromatase-overexpressing MCF-7, and LTEDaro ER + BC cell lines  | Autophagy as a cytoprotective mechanism in acquired resistance to AIs, inhibition of autophagy and/or the PI3K pathway restored AI sensitivity   | [38]                                     |
| Trastuzumab<br>(lapatinib)<br>(erlotinib)<br>(gefitinib) | TKI              | HER2              | early stage or metastatic HER2 + BC, usually in combination with chemotherapy or alone after chemotherapy   | MCF-7, T-47D, ZR75-1, MDA-MB-231, HCC38, HCC1806, MDA-MB-157<br>MCF-7 xenograft mouse models<br>BC PDX mouse models<br>Data set analysis (TCGA)<br>SKBR-3 (sensitive and trastuzumab-resistant) HER2 + BC cell line | BC cells activate autophagy after CDK4/6 inhibition as an escape mechanism from apoptosis. Palbociclib combined with autophagy inhibition decreased proliferation of cells <i>in vitro</i> and tumor growth <i>in vivo</i><br><br>Autophagy is enhanced in trastuzumab-resistant cells and its inhibition sensitized cells to trastuzumab  | [45]<br>[49]                             |
| Lapatinib  | TKI              | EGFR<br>HER2      | In combination with capecitabine or trastuzumab in advanced/metastatic BC patients                          | BT-474 and MCF-7<br>adherentHER2 + BC cells and spheroids   | 3D culture of BT-474 cells allowed formation of a protective microenvironment against trastuzumab, which could be overcome by the administration of autophagy inhibitors.  | [136]                                    |
| Enzalutamide   | Antiandrogen     | Androgen receptor | Adult metastatic/no metastatic patients to a high level of risk CRPC  | JIMT-1 and SKBR-3 HER2 + BC cell lines<br>JIMT-1 BCxenograft mouse model  | Knockdown of ATG genes inhibited intrinsic resistance to trastuzumab, lapatinib, erlotinib and gefitinib. Treatment of JIMT-1 xenografts with trastuzumab + CQ and trastuzumab treatment of ATG12-silenced xenografts reduced tumor growth   | [51,54]                                  |
| Abiraterone acetate (AA) (ZYTUGA)                        | Antiandrogen     | CYP17<br>LHRH     | Metastatic hormone sensitive prostate cancer, mHSPC /metastatic castration resistant prostate cancer, mCRPC | SKBR-3 and BT-474 HER2 + BC cell lines (both sensitive and trastuzumab-resistant)<br>Patient clinical data and tissue samples<br>MCF-7 and MDA-MB-468 HER2 + BC cell lines  | P130Cas protected HER2 from autophagic degradation by impairing its ubiquitination, thus conferring resistance to trastuzumab. P130Cas expression increased in tumor samples from patients who developed resistance to trastuzumab treatment.  | [55]                                     |
| Everolimus   | mTORi            | mTOR<br>VEGF      | sensitive prostate cancer, mHSPC /metastatic castration resistant prostate cancer, mCRPC                    | LNCaP   | Inhibition of eEF-2 reduced pro-survival autophagy and increased response to trastuzumab, lapatinib and gefitinib.<br>Beclin-1 binds HER2 and promotes its phosphorylation. Lapatinib blocks this interaction, allowing the induction of autophagy by Beclin-1.<br>Autophagy inhibition enhances lapatinib sensitivity of lapatinib-resistant cells.<br>Under enzalutamide treatment transmission electron microscopy induces an increase of autophagy vesicles (AVs) (induced by autophagy upregulation), confirming from the expression of the autophagy-proteins LC-3, ATG5 and Beclin 1 is increased while p62 is reduced. | [50]                                     |
|  |                  |                   |   |   | AA increased autophagy in LNCaP cells demonstrated by the upregulation of ATG5 and LC3 and accumulation autophagosomes.<br>Everolimus (EVS) used against (CRPC), there is a correlation between NPRL2 and EVS, NPRL2 overexpression induced tumor cell proliferation, resistance to EVS, whereas NPRL2 silencing inhibited proliferation. NPRL2 silencing promoted the activity enhanced mTOR signaling, and the decrease of autophagy   | [137]<br>[53]<br>[119]<br>[123]<br>[118] |

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| DRUG                | CLASS                        | TARGET   | CANCER SUBTYPE AND STAGE OF TREATMENT  | EXPERIMENTAL MODEL  | AUTOPHAGY MECHANISM/EFFECT  | REF      |
|---------------------|------------------------------|--|--|---|---|----------|
| <b>COLON-RECTUM</b> | Bevacizumab                  | VEGF   |  | HT-29<br>Mice   | induced by NPRL2- silencing in EYS-treated CRPC cells was associated with the increase of apoptosis. Bevacizumab promoted autophagy, as evidenced by the appearance of autophagic vacuoles. | [61]     |
|                     | Cetuximab                    | EGFR   |  | HT29  | Apatinib induced autophagy in colon cancer cells.   | [64,65]  |
|                     | Apatinib<br>(YN968D1)        | VEGFR-2  |  | HCT116<br>MICE  | inhibiting autophagy could stimulate ER stress associated CRC cell apoptosis both <i>in vitro</i> and <i>in vivo</i> , suggesting a protecting role of apatinib induced autophagy           |          |
|                     | Cabozantinib<br>(XL184)      | MET  |  | HCT116  | The inhibition of multiple kinase pathways produces a change in metabolism from glycolysis to autophagy   | [99,102] |
| Sorafenib           | VEGFR2<br>BRAF/CRAF<br>VEGFR | *Not responders HCC patients or not eligible for surgery | HT29<br>HCC  | Autophagy is responsible for orchestrating adaptive responses to sorafenib in HCC. Inhibition of autophagy using either pharmacological inhibitors (chloroquine, 3-MA or baflomycin A1) or essential autophagy gene (Beclin1 or Atg5) knockdown enhances the cytotoxicity of sorafenib against HCC cells, indicating that autophagy induced by sorafenib acts as a protective pathway |   |          |
| <b>LIVER</b>        | Imatinib                     | BCR-Abl<br>C-Kit   | *First line in CML/ALL (Ph + ) patients  | Human CML K562 cell line  | miRNA-30a induces apoptosis by inhibiting pro-autophagic genes expression (ATG-5 and Beclin-1)  | [75]     |
|                     | Dasatinib                    | PDGF<br>BCR-Abl<br>EPH                                   | *Second Line in CML/CLL patients   | p53 <sup>wt</sup> /p53 <sup>del17</sup> primary CLL<br>Lymphocytes  | Mutated p53 form inhibits autophagy resistance mechanism  | [76]     |
|                     | Ponatinib                    | PDGFβ<br>BCR-abl<br>RET                                  | * In LMC/LLA <sup>Phs/NH-Res</sup> (Ph + ) or T3151 mutated patients   | Human KCL22 <sup>Phs-Res</sup><br>PDX mouse models  | Alternative mTOR target strategies sensitize TKI-resistant CML cells  | [138]    |
|                     | Perifosine                   | FGFR<br>c-KIT<br>VEGFR                                   | ** Clinical Trial Phase II on refractory/relapsed LMC Patients   | Human AML Kasumi-1, HL-60<br>Human CML K562   | Perifosine-induced Autophagy due to up-regulation of ATG5   | [77]     |
| <b>LYMPHOMA</b>     | Vorinostat                   | HDAC   | ** Clinical Trial Phase II on AML/MDS patients   | AML-CLs Kasumi-1 <sup>(8;21)</sup> ; SKNO-1 <sup>†</sup><br>(8;21); HL60  | Autophagy is activated by HDACi vorinostat in response to the accumulation of ubiquitinated proteins among which AML-ETO1.  | [78]     |
|                     | Bortezomib                   | Proteasome 26S   | * In MCL patients not eligible for ASCT  | Primary human AML-CL<br>DLBCL derived ABC (su-DHL 8) and<br>GCB (su-DHL 4) cell lines   | The Bortezomib induced autophagy leads to a gained IκBα degradation with related up-regulation of NF-κB-regulated genes involved in the resistance  | [81]     |
|                     | Everolimus                   | mTOR<br>FKBP-12  | * In MCL patients not eligible for ASCT  | DLBCL derived ABC (su-DHL 8) and<br>GCB (su-DHL 4) cell lines   | The complex D1/CDK4 inhibits autophagy induced by Bortezomib, which in this way cannot lead to the NOXA degradation   | [82]     |
|                     | Temsirolimus                 | mTOR<br>FKBP-12  | ** Clinical phase II trials on patients with w relapsed/refractory HL that has progressed after high-dose chemotherapy or ASCT | Primary effusion lymphoma cell line   | Bortezomib induces a pro-survival autophagy activation, correlated with the expression/degradation of ER stress protein CHOP, BP, and JNK   | [83]     |
|                     | Crizotinib                   | ALK<br>HGFR  | * Adult MCL patients refractory/relapsed   | MCL-CL  | Autophagy induced by drug promotes resistance by blocking the AKT-mTOR targeting  | [84]     |
|                     |                              |  | ** Clinical phase I/II trial on younger ALCL patients  | BL-CL Namalwa, Raji, Daudi, Ramos, and DLBCL-CL   | The co-administration of Temsirolimus with HDACi enhances the cytotoxic effect on tumor cells by the inhibition of autophagy  | [85]     |
|                     |                              |  |  |   | Pharmacological or genetic autophagy inhibition potentiates the anti-tumoral activity of ALK inactivation.  | [86]     |

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Table 1 (continued)

| DRUG                  | CLASS  | TARGET   | CANCER SUBTYPE AND STAGE OF TREATMENT   | EXPERIMENTAL MODEL   | AUTOPHAGY MECHANISM/EFFECT   | REF       |
|-----------------------|--------|--|---|--|--|-----------|
| Milutuzumab           | mAb    | c-Met<br>ROS1                                  | ** Clinical phase I/II trial on relapsed/refractory B-cell NHL  | Karpas-299 <sup>(2;5)</sup> and SU-DHL-1 <sup>(2;5)</sup> ALK-positive ALCL-CLs and ALCL mouse models  | Milutuzumab cytotoxicity is promoted by FTY720 which inhibits the autophagy-mediated degradation of CD74   | [87]      |
| Bortezomib            | UPSi   | CD74<br>Proteasome 26S                         | *Treated MM patients in progression, not eligible for ASCT or MM patients not eligible for any treatment. | Primary human MCL-CLs and mouse models<br>Primary MM-CLs Bim <sup>hi</sup> /Bim <sup>low</sup>   | Bim shows a dualistic role in Bortezomib resistant MM cells Bim <sup>hi</sup> /Bim <sup>low</sup> . The blockade of autophagy regulates alternatively the activation/inhibition of this apoptosis inducer  | [89]      |
|                       |        |  |   | MM-CLs   | Bortezomib induces cytoprotective autophagy GRP78-mediated to increase the degradation of the accumulated unfolded protein.  | [90]      |
| Carfilzomib           | UPSi   | Proteasome 20S                                 | *Adult MM patients after first-line therapy   | MM-CLs ANBL-6, INA-6, and JJN3   | Carfilzomib induces permanently elevated levels of SQSTM1 protein involved in autophagosome formation and misfolded protein degradation.   | [91]      |
| Sorafenib             | TKI    | BRAF/<br>CRF/VEGFR<br>PDGFR<br>FLT-3<br>FGFR-1 | ** Sorafenib in treating patients with relapsed or refractory MM  | CD138 + hMM-CLs OPM-2, U-266, LP1, NCI-H929, Karpas 620, and RPMI-8226;<br>5T33MM-CL mouse models<br>Clinical study on MM patients bone marrow samples | Sorafenib inhibits ERK activation but contemporary induces cytoprotective autophagy activation, with related up-regulation of anti-apoptotic Mcl-1 protein   | [139]     |
| Trametinib            | MEKi   | MEK1/2   | ** Trametinib and HQC in treating patients with pancreatic cancer   | PDAC-CLs Mia-PaCa2, BxPC3 or PDX220 <sup>KRAS mut</sup><br>PDA mouse models with KRAS <sup>wt/</sup> mutated cell lines                                | The combination of MEK1/2 inhibition plus autophagy inhibitor increases the regression of PDA-CLs RAS mutated.   | [111]     |
| Binimetinib           | MEKi   | MEK1/2   | ** Binimetinib and HQC in treating patients with KRAS mutant metastatic pancreatic cancer                 | hPDAC-CLs Pa01C, Pa02C, Pa04C, Pa14C and Pa16C   | Acute KRAS/ERK suppression increased autophagy by impairing metabolic processes  | [114,115] |
| PLX4720 (Vemurafenib) | B-RAFI | B-RAF  | Used in melanoma patients with mutation BRA-F V600E   | Murine derived iKRAS cell line<br>A375<br>A375p<br>SKMEL5,<br>MEL1617<br>Mice  | The blockade of BRAF combined with the pharmacological inhibition of Autophagy could be an important strategy to improve the efficacy of Vemurafenib on cells resistant to it, <i>in vitro</i> but also <i>in vivo</i> .   | [114,115] |
| Dabrafenib            | B-RAFI | B-RAF  | Used in melanoma patients with mutation BRA-F V600E, in clinical it is used with trametinib               | A375<br>MEL624 <sup>B-RAFres</sup>   | Autophagy is regulated by ER stress, they found a significantly PERK protein level reduction, after treatment with PERK siRNA in both A375 and MEL624 cells. The viability assay demonstrated that Dabrafenib group was more resistant to the treatment in comparison to the cotreatment group. These findings support the protective role of autophagy in melanoma cells to Dabrafenib treatment. | [116]     |

\* <http://www.ema.europa.eu>.\*\* <https://clinicaltrials.gov>.



*In vivo* studies have shown that CQ and H19 knockdown restored the antiestrogen-sensitivity in TAM-resistant xenografts [37,42].

Cyclin-dependent kinase 4/6 (CDK4/6) inhibitors including palbociclib have been approved for the treatment of advanced ER + human epidermal growth factor receptor 2 (HER2)-negative BC in combination with an AI or fulvestrant [44]. Vijayaraghavan et al. showed that palbociclib activated autophagy in MCF-7 cells *in vitro* and *in vivo*. Inhibition of autophagy (HCQ, CQ, Lys05, Spautin-1, bafilomycin A1 or Beclin 1 /ATG5 knockdown) sensitized the cells to CDK4/6 inhibitors including palbociclib [45] and combined treatment induced senescence *in vitro*. *In vivo*, the combination of palbociclib with HCQ or Lys05 led to a massive growth reduction of xenograft tumors. Based on these results a clinical trial is currently evaluating the efficacy of neoadjuvant letrozole and palbociclib with HCQ in ER + HER2- BC (ClinicalTrials.gov Identifier: NCT03774472).

#### HER2-targeted therapy

HER2-positive tumors comprise approx. 25% of BC cases and correlate with an aggressive phenotype and poor prognosis [46]. However, the development of HER2-targeted therapy represents a milestone in the treatment of this BC subtype and by now several agents targeting HER2 are available: the mAbs trastuzumab and pertuzumab, mAb-drug conjugates like trastuzumab, and the TKIs lapatinib and neratinib [47,48]. HER2-targeted therapy is usually combined with chemotherapy, often in a neoadjuvant and adjuvant setting [31]. Unfortunately, 70% of patients develop resistance to trastuzumab treatment within a year [47].

Trastuzumab as well as lapatinib have been shown to induce autophagy *in vitro* [49,50], and cell lines with intrinsic or acquired resistance to trastuzumab [49,51,52] or lapatinib [53] exhibit increased basal autophagy.

Vazquez-Martin et al. observed that in trastuzumab-resistant HER2 + SKBR-3 cells the enhanced basal autophagy was further increased by trastuzumab treatment. Autophagy inhibition with 3-MA reduced viability and siRNA-mediated knockdown of LC3 decreased proliferation and re-sensitized the cells to trastuzumab [49]. Also HER2 + JIMT-1 cells intrinsically resistant to HER2-targeting drug, treatment with CQ or knockdown of ATG genes re-sensitized the cells to trastuzumab as well as lapatinib [54].

In a screen of more than 50 BC cell lines, Cufi et al. found that the autophagy protein ATG12 is commonly up-regulated in trastuzumab-resistant HER2-overexpressing cell lines. ATG12 silencing reduced the resistance of JIMT-1 cells to trastuzumab, lapatinib, erlotinib and gefitinib *in vitro*. *In vivo*, ATG12-silenced JIMT-1 xenografts exhibited markedly reduced tumor growth and trastuzumab treatment decreased tumor growth massively [51]. Also LC3 knockdown increased the sensitivity of JIMT-1 cells to trastuzumab, lapatinib, erlotinib, and gefitinib [52]. The combination of trastuzumab with CQ increased apoptosis and reduced cell viability and colony formation of JIMT-1 cells *in vitro* and decreased tumor volume by 90% *in vivo* [52]. In lapatinib-resistant BT-474 and AU-565 cell lines combination of CQ or 3-MA with lapatinib decreased cell proliferation and colony formation and enhanced apoptosis [53].

One of the mechanisms of action of trastuzumab involves the binding-mediated degradation of HER2. Bisaro et al. found that the p130Cas, a signaling protein involved in adhesion, migration and invasion, protects HER2 from being degraded by autophagy by preventing its ubiquitination. P130Cas is elevated in trastuzumab-resistant HER2 + BT-474 and SKBR-3 cell lines and histological samples of trastuzumab-unresponsive BC patients [55].

Taken together, all the described studies indicate that autophagy plays a major role in mediating resistance to targeted therapies for HER2-positive BC. This is supported by the observation that loss of the BECN1 gene encoding Beclin 1 correlates with an improved clinical response to trastuzumab [58]. Hence, autophagy inhibition in

combination with targeted therapy for HER2-positive BCs is a promising path that should be evaluated in clinical trials. Nevertheless, caution should be taken as the role of autophagy in BC is controversial. There are also results showing that in lapatinib-sensitive BT-474 and AU-565 cells 3-MA treatment reduced the cytotoxic effect of lapatinib because in this case lapatinib-induced autophagy promoted apoptosis [56].

#### Colorectal cancer

Colorectal cancer (CRC) is one of the most diagnosed cancer worldwide being the fourth in United States. The incidence of CRC has declined in the last 40 years from 60.5 per 100.000 in 1976 to 40,7 in 2013, as well as the peak mortality has decreased from 28,6 in 1976 to 14.1 in 2014. Despite this, CRC represents a leading cause for cancer death worldwide [57].

The targeted therapies proven most effective in the treatment of CRC are targeting angiogenesis (e.g. bevacizumab, apatinib, cabozantinib) and the epidermal growth factor receptor (EGFR) (e.g. cetuximab) (Table 1) [58]. Bevacizumab is a recombinant humanized monoclonal antibody that binds to vascular endothelial growth factor A (VEGF-A) and blocking the VEGF-receptor 2 (VEGFR2) signaling [59,60]. Zhao et al. showed that bevacizumab induces autophagy in CRC cell lines, as evidenced by the appearance of autophagic vacuoles, punctate patterns of LC3 and the accumulation of Beclin 1. Inhibiting autophagy using CQ or RNA interference targeting Beclin 1 and ATG5 promotes bevacizumab-induced apoptosis and inhibits proliferation, suggesting that autophagy plays a protective role. The same results were obtained *in vivo*: inhibiting autophagy using CQ or small interfering RNA in combination with bevacizumab significantly inhibits tumor growth *in vivo* compared to bevacizumab alone. In the same study, bevacizumab increases hypoxia-inducible factor 1 $\alpha$  (HIF-1 $\alpha$ ) expression. HIF-1 $\alpha$  inhibition (YC-1) markedly reduced autophagy. These results suggest that hypoxia-induced autophagy in tumor cells may function as an adaptive response to hypoxia caused by anti-angiogenic therapy [61].

Apatinib (investigational compound YN968D1) is a TKI of the vascular endothelial growth factor receptor-2 (VEGFR2) [62]. It also inhibits other TKs such as c-Kit and c-SRC TKs, and reduces ABCB1 and ABCG2 transporters [63]. Lu et al. presented the first evidence that apatinib induces autophagy in colon cancer cells by inhibiting the AKT-mTOR signaling pathway [64]. Cheng et al. discovered that apatinib directly induces ER stress stimulating autophagy through the upregulation of the Inositol-requiring enzyme 1 (IRE1) signaling pathway. Meanwhile, inhibiting autophagy could stimulate ER stress-associated CRC cell apoptosis both *in vitro* and *in vivo*, suggesting a protective role of apatinib-induced autophagy. Blocking autophagy using CQ or a siRNA targeting ATG5 could significantly induce apoptosis in CRC cell lines *in vitro*. Additionally, the combination of CQ with apatinib has a greater suppressive effect in subcutaneous xenografts in nude mice compared with apatinib or CQ alone [65].

Cabozantinib (XL184) is an orally bioavailable inhibitor of multiple kinases involved in cell growth, angiogenesis and metabolism including VEGFR2/KDR, MET, AXL, RET, TIE2, and c-Kit. MET and VEGFR2 dual inhibition is central for cabozantinib effects [69]. Scott et al. observed a significant increase in autophagy following cabozantinib treatment in the HCT116 and HT29 CRC cell lines [66]. The inhibition of multiple kinase pathways produces a metabolic dysregulation, with a reduction of glycolysis leading to cell death. In this context autophagy act as a salvage mechanism promoting drug resistance. A combination of cabozantinib with autophagy inhibitors increases apoptosis in HCT116 and HT29 cell lines [66].

Cetuximab is a chimeric, anti-EGFR monoclonal IgG1 class antibody. It blocks EGFR signaling and modulates tumor cell growth by inhibiting proliferation, angiogenesis, and differentiation, and preventing metastasis [67,68]. Li et al. found that cetuximab induces

autophagy by two different mechanisms involving PI3K type I and type III. The EGFR/class-PI3K/Akt/mTOR signaling pathway normally inhibits autophagy, and by disrupting this signal cetuximab activates autophagy. Moreover, cetuximab decreases BCL-2 through HIF-1 downregulation, this releases beclin 1 to form a complex with class III PI3K, which directedly induces autophagy [69]. PI3K-AKT-mTOR signaling pathway is one of the most dysregulated pathways in cancer as it regulates many cellular processes such as metabolism, motility and growth. For this reason, about 40 different inhibitors are being evaluated at different stages of clinical research [70]. Class III PI3K plays a fundamental role in autophagy, vesicular trafficking and phagocytosis, however, its role in cancer still remains elusive [70]. In the same direction, Guo et al. demonstrated that cetuximab induces autophagy in Caco-2 CRC cells [71].

## Hematologic malignancies

**Leukemia** is cancer of the body's blood-forming tissues, including the bone marrow and the lymphatic system. There are different kinds of leukemia depending on the hematopoietic lineage and maturity of the aberrant cells. However, the most common kinds are acute myeloid leukemia (AML), acute lymphoid leukemia (ALL), chronic myeloid leukemia (CML) and chronic lymphoid leukemia (CLL) [72]. Typically, most forms of leukemia are treated with a standard multi-drug regimen for myelosuppression: anthracycline, alkylating agents (cyclophosphamide), corticosteroids and vinca alkaloids (vincristine). Targeted therapies are currently used mainly in CML, where the standard treatment includes imatinib, a TKI targeting BCR-ABL (Philadelphia Chromosome disease), c-Kit and platelet-derived growth factor (PDGF) receptors (Table 1) [73]. Recent studies highlight the role of autophagy in the resistance to this drug. Yu et al. demonstrated that imatinib inhibits the expression of miR-30a in CML patients primary cell lines [74]. miR-30a negatively regulates autophagy by directly targeting Beclin 1 and ATG5, thus its inhibition increases autophagy. Knockdown of Beclin 1 and ATG5 by miR30 or using shRNA reestablish imatinib cytotoxic effect [75]. Administration of other TKIs, such as dasatinib and ponatinib increases autophagy as a drug resistance mechanism. A study by Amrein et al. demonstrated that dasatinib induces autophagy in CLL primary lymphocytes and that CQ re-sensitize the cells [76]. Similarly, Mitchel et al. highlighted that ponatinib induces BCR-ABL-independent resistance in CML cells, through alternative activation of mTOR signaling. The pharmacological or genetic blockade of mTOR and autophagy enhanced the sensitivity of ponatinib-resistant CML cells to cell death *in vitro* and *in vivo* [80]. Similarly, Tong et al. showed that autophagy inhibition can re-sensitize CML cells to perifosine, which targets PI3K/AKT/mTOR signaling pathway [77].

One more example in the context of AML is given by Torgersen et al. They showed that in AML1-ETO-positive AML cells, apoptosis induced by histone deacetylase (HDAC) inhibitors valproic acid and vorinostat is limited by the upstream activation of autophagy. Blocking autophagy results in enhanced caspase activity and apoptotic cell death [78].

**Lymphoma** is a heterogeneous group of chronic malignancies characterized by different etiopathogenesis, clinical behavior and response to treatment. Typically, the aberrant proliferation of precursor/mature lymphoid cells is restricted to lymphatic organs [79]. Lymphoma treatment depends on the tumor subtype and stage. Typically, for the more aggressive forms, the standard approach is CHOP (cyclophosphamide, doxorubicin, vincristine, and prednisone) or CHOP-like combination chemotherapy, which can be combined with anti-CD20 mAb therapy (rituximab plus/or obinutuzumab) [80].

In the last decades, many molecular targeted therapies (mAbs or small molecule inhibitors) have been developed to treat lymphomas. For instance, bortezomib is a proteasome inhibitor that can kill cancer cells by blocking I $\kappa$ B $\alpha$  degradation, resulting in NF- $\kappa$ B inhibition, or by preventing the degradation of pro-apoptotic proteins. Recent studies on activated B-cells and germinal center B-cells derived from diffuse large

B-cell lymphoma (DLBCL) (su-DHL 8 and su-DHL 4) demonstrated that bortezomib antagonizes the constitutive activation of NF- $\kappa$ B induced by TNF- $\alpha$  or TRAIL. Bortezomib resistance is mediated by the activation of the autophagy machinery, which is necessary for the degradation of many ubiquitinated proteins, including I $\kappa$ B $\alpha$ . Autophagy block using CQ reverted the resistance by preventing I $\kappa$ B $\alpha$  degradation and restored NF- $\kappa$ B activity [81]. Using the same approach, Heine et al. also explained that in D1/CDK4-aberrant mantle cell lymphoma (MCL) cell lines (Mino, Jeko-1, Rec-1, Jvm2, and Granta-519) exposed to bortezomib, the pro-apoptotic protein NOXA is efficiently expressed only when the D1/CDK4 complex inhibits autophagy, otherwise NOXA gets degraded [82]. Also, Granato et al. found that bortezomib induces the upregulation of proteins involved in ER stress and apoptosis (CHOP, BIP, and JNK) in primary effusion lymphoma cell lines. The pro-survival role of autophagy could be reversed by the administration of autophagy inhibitors or by the silencing of ATG genes [83].

The mTOR kinase inhibitors everolimus and temsirolimus have shown strong cytotoxicity in pre-clinical and clinical models of some hematological malignancies. Rosich et al. demonstrated that, in MCL cell lines, everolimus-induced autophagy promoted resistance by preventing AKT-mTOR targeting. This effect was reversed by genetic or pharmacological autophagy inhibition with CQ or ATG gene knock-down [84]. Moreover, Dong et al. showed that the HDAC inhibitor valproic acid (VPA) increased temsirolimus efficacy on Burkitt lymphoma (BL) cell lines (Namalwa and Raji) through autophagy and MYC inhibition. The authors confirmed the results also in pre-clinical mouse models of BL, reporting a significant decrease in tumor growth and contemporary MYC inhibition in the group receiving a combination of temsirolimus and an HDAC inhibitor [85].

Recent studies have shown that ALK-expressing anaplastic large cell lymphoma cells treated with ATP-competitive inhibitors targeting ALK and c-Met develop autophagy-mediated resistance. Mitou et al. demonstrated that crizotinib inactivated ALK, thereby increasing autophagy, which plays a pro-survival role and could be counteracted by the administration of autophagy inhibitors [86]. A very interesting study by Alinari et al. reported that FTY720 (fingolimod) and milatuzumab (anti-CD74 mAb) act synergistically on MCL cell line. FTY720 leads to increased expression of CD74 by blocking its autophagy-mediated degradation, thus increasing mAb efficacy [87].

**Multiple Myeloma (MM)** is a cancer originating from terminally differentiated plasma cells. The patients show bone marrow infiltration of clonal cells and the presence of monoclonal antibodies in the peripheral blood [88]. Standard treatments include a combination of bortezomib and lenalidomide which increased the five-year survival to 49% in the last years [88]. Chen et al. have demonstrated that bortezomib-resistant cell display Bcl-2-like protein 11 (Bim) downregulation. HDACis and BH3 mimetics can revert the resistance by increasing Bim levels but this was correlated with Bim-associated autophagy regulation. Indeed, CQ was required to induce cell lethality [89]. Also, Jagannathan et al. have shown that bortezomib activates autophagy as a compensatory mechanism for the accumulation of unfolded proteins. Moreover, they have reported that the co-administration with metformin suppressed glucose-regulated protein 78 (GRP78), a key effector of bortezomib-induced autophagy, thus enhancing apoptosis [90]. Recent studies on MM demonstrated that carfilzomib, an irreversible proteasome inhibitor, induces overexpression of SQSTM1/p62, a cargo protein associated with autophagosomes. Co-administration with CQ sensitizes MM cells to the targeted therapy [91].

## Liver cancer

Hepatocellular carcinoma (HCC) is the most common type of primary liver cancer [92]. Currently, surgical resection is recommended for very early stage and early stage HCC following chemo-/radiotherapy, but HCC is still prone to recurrence and metastasis after surgery and there is still no effective treatment for patients with advanced,



metastatic or drug-resistant HCC [93,94]. Therefore, it is essential to elucidate the mechanisms of tumorigenesis, metastasis, and drug resistance in HCC and to identify effective and safe therapeutic strategies and prognostic biomarkers [95]. In HCC, autophagy inhibition in combination with targeted therapy have shown a great potential in improving the efficacy on tumor cells while having a lesser effect on normal cells (Table 1) [96]. This provides the foundation for promising targeted therapy for HCC through autophagy inhibition.

Sorafenib (BAY 43–9006, Nexavar®), an oral multi-kinase inhibitor, remains the only FDA approved systemic drug for patients with advanced HCC [97,98]. Studies have shown that sorafenib treatment enhances autophagy in HCC cells, and is responsible for orchestrating adaptive responses to sorafenib. Inhibition of autophagy using either pharmacological inhibitors (CQ, 3-MA or bafilomycin A1) or knock-down of essential autophagy genes (Beclin 1 or ATG5) enhances the cytotoxicity of sorafenib in HCC cells, indicating that autophagy induced by sorafenib acts as a protective mechanism [99–102]. Shi et al. found that direct stimulation of ER stress by sorafenib in HCC cells induces autophagy via the upregulation of the IRE1 pathway and that inhibition of autophagy promotes ER stress-related apoptosis of HCC cells *in vitro* and *in vivo*. These results support the hypothesis that sorafenib-induced ER stress signals are critical for the induction of autophagy. Their data indicate that all the chemical and genetic autophagy inhibitors, 3-MA, CQ and ATG5 siRNA knockdown, potentiate sorafenib-induced cell death. They have also demonstrated that inhibition of autophagic degradation resulted in ER stress potentiation. Therefore, sorafenib-induced autophagy alleviated ER stress, diminishing the apoptotic signals and thus suppressing cell death [99].

## Lung cancer

Lung cancer is the deadliest type of cancer worldwide with 1.7 million deaths each year [103]. It is classified into two groups: small cell lung carcinoma (SCLC) and non-small cell lung carcinoma (NSCLC), which make up 15% and 85% of lung cancer cases, respectively [104]. NSCLC is classified into squamous cell carcinoma (30%), large cell carcinoma (10%) and adenocarcinoma (40%) [105].

Standard treatment involves surgery followed by adjunct chemotherapy or radiation.

A large variety of drugs have been approved for targeted therapy in lung cancer: anti-angiogenic drugs, inhibitors targeting mutated proteins like EGFR, ALK, ROS1, and BRAF (Table 1).

Autophagy is well described as a mechanism of resistance to targeted therapy in lung cancer. The anti-angiogenic mAb bevacizumab synergizes with the proteasome inhibitors MG132 or bortezomib, which are also known to block autophagic flux, in lung cancer cells both *in vitro* and *in vivo*, suggesting a role in bevacizumab resistance. Studies [106,107] have shown that treatment with erlotinib, an EGFR TKI, induces autophagy in EGFR-mutated cell lines. In a non-sensitive EGFR wild type cell line, blocking autophagy with CQ decreases cell viability. Goldberg et al. [108] performed a phase 1 clinical trial treating NSCLC patients with HCQ with and without erlotinib and found that HCQ with or without erlotinib is safe and well-tolerated. Another clinically approved EGFR inhibitor, afatinib, was found to act synergistically in combination with CQ and 3-MA in EGFR-mutated NSCLC cell lines (H1975 and H1650) both *in vitro* and *in vivo* [109]. Crizotinib (PF02341066), an inhibitor of the ALK fusion oncoprotein, is clinically approved for the treatment of ALK-positive NSCLC patients. Its effectiveness is reduced after approximately a year of treatment due to the onset of resistance of the tumor. It was found that crizotinib-resistant cells downregulate ALK expression due to autophagy upregulation and the combination with CQ was able to overcome resistance [110]. Vismodegib, an inhibitor of the sonic hedgehog homolog pathway, is already used in lung adenocarcinoma (LUAD). A study has shown that vismodegib increases autophagy in LUAD cell lines and that the inhibition of autophagy with siRNAs targeting ATG5 or ATG7 increases

its antiproliferative effect *in vitro*. Furthermore, its combination with CQ enhances anti-LUAD efficacy *in vivo*. The FDA has approved the BRAF inhibitor dabrafenib in combination with the MEK inhibitor trametinib for patients with BRAF<sup>V600E</sup> NSCLCs. Kinsey et al. found that in BRAF<sup>V600E</sup> cell lines (BxPC3) trametinib increases autophagic flux and its inhibition by CQ enhanced cytotoxicity [111]. Karsli-Uzunbas et al. conditionally deleted ATG7 in adult mice. Interestingly, acute autophagy ablation in mice with preexisting NSCLC blocked tumor growth, promoted tumor cell death, and inhibited more benign disease (oncocytomas) [112].

## Melanoma

Melanoma is one of the main causes of cancer-related death worldwide, representing the most invasive and metastatic skin tumor type. Unfortunately, only a small proportion of patients with metastatic melanoma survive more than 10 years after the diagnosis of the disease. There are different types of targeted therapy approved by the FDA for melanoma with mutations in the BRAF gene, which result in the constitutive activation of the RAS/RAF/MEK/ERK pathway (Table 1). They include inhibitors targeting BRAF directly (vemurafenib, dabrafenib, encorafenib) or the MEK proteins (trametinib, cobimetinib, binimetinib) which act downstream of BRAF. In most cases, patients with a BRAF mutation receive both a BRAF and a MEK inhibitor, as combining these drugs often shows better response [113].

Recent studies have demonstrated the ability of BRAF inhibitors to induce autophagy as part of a transcriptional program that upregulates lysosome biogenesis/function, driven by the TFEB transcription factor. In BRAF<sup>V600E</sup>-mutated xenografts, TFEB was inactivated independently from mTORC1, associated with high levels of TGF- $\beta$  and more aggressive histopathological features [114]. BRAF inhibition activates JNK2/p38, which in turn phosphorylates ZKSCAN3, alleviating the repression of TFEB and increasing the production of lysosomal/autophagic factors. ZKSCAN3 (ZNF306) belongs to a family of zinc-finger transcription factors harboring KRAB and SCAN domains. It is a transcriptional repressor of the autophagy–lysosome network, and is regulated in conjunction with TFEB during starvation/lysosome activation. Inhibition of autophagy or the lysosomal pathway increases TGF- $\beta$  levels, which leads to increased tumor aggressiveness. Treatment of the human melanoma cell line A375 expressing BRAF<sup>V600E</sup> with the BRAF inhibitor PLX4720, a progenitor of vemurafenib, leads to increased levels of the autophagy marker LC3 and degradation of p62 in a dose-dependent manner. The authors have highlighted that the BRAF<sup>V600E</sup>-TFEB/ZKSCAN3-autophagy-lysosomal axis is a signaling pathway that works together with TGF- $\beta$  and the EMT machinery, inducing tumor progression, metastasis and resistance to BRAF-targeted therapy in melanoma [114].

The evaluation of autophagic markers in different BRAF inhibitor sensitive (A375P, SKMEL5, MEL1617) and resistant (MEL1617R, WM983BR, MEL624) human melanoma cancer cell lines confirmed that after treatment with the BRAF inhibitor PLX4720, LC3-II/LC3-I ratio is significantly increased and p62 insignificantly reduced in all cell lines [120]. Ma et al. have demonstrated that treatment of these cell lines with vemurafenib induces binding of the mutant BRAF to the ER stress gatekeeper GRP78, which rapidly increases ER stress. Dissociation of GRP78 from the PKR-like ER-kinase promotes the PERK-dependent ER stress response which activates cytoprotective autophagy. In this system, combined BRAF and autophagy inhibition (HCQ) promotes tumor regression in BRAF inhibitor-resistant xenografts [115].

Treatment with the BRAF inhibitor dabrafenib induces a dose-dependent activation of autophagy in both sensitive (A375) or resistant (MEL624) human melanoma cell lines. In this context, dabrafenib activates ER stress-dependent autophagy, whereas PERK silencing attenuated autophagy. Autophagy inhibition (3-MA) increases the dabrafenib effect and restores sensitivity in resistant cell lines [116]. Xie et al. deleted ATG7 in BRAF<sup>V600E</sup>-mutated melanoma cells [122] showing

that ATG7 deficiency in melanoma xenografts dramatically increases the survival of these mice. BRAF<sup>V600E</sup> inhibition results in larger tumor volume reduction in ATG7 null mice [117]. In conclusion, autophagy plays a key role in the resistance of BRAF mutant melanoma to BRAF inhibitors. Mutant BRAF can induce resistance to BRAF inhibitors through autophagy in multiple ways, including the subsequent increase in ATP synthesis, oxidative stress or ER stress. Therefore, autophagy can be considered a potential therapeutic target.

### Prostate cancer

Prostate cancer (PC) is the most common cancer in men. While most types of prostate cancer grow slowly and may need minimal or even no treatment, other types are aggressive and can spread quickly.

The mTOR inhibitor everolimus is an important drug used in the treatment of prostate cancer, in particular for castration-resistant prostate cancer (CRPC) (Table 1). NPRL2 expression is upregulated in PC, particularly in CRPC where it induces tumor cell proliferation and resistance to everolimus. NPRL2 silencing inhibits proliferation, enhances mTOR signaling and decreased autophagy, which is associated with an increase in apoptosis [118].

Androgen deprivation or treatment with the anti-androgens enzalutamide or bicalutamide increased autophagic flux in PC cells *in vitro* and in PC models *in vivo* [119]. This effect is reduced by the knockdown of ATG5 and Beclin 1 or inhibition of the androgen-induced mTOR pathway [120]. Treatment with EPI-001 (EPI), an androgen receptor inhibitor, reduces cell growth and increases apoptosis in PC cells. Also, EPI-treated cells showed increased autophagosome formation [121]. The combination of EPI with autophagy inhibitors further reduces cell viability significantly. Therefore, this combination may offer a strategy to overcome resistance mechanisms in advanced PC [121].

Androgen deprivation therapy is a common therapy used in the clinic to treat PC, but in CRPC the remaining low levels of androgens are sufficient to activate androgen receptor signaling, which can be altered on several levels. Under enzalutamide treatment transmission electron microscopy has shown an increase in autophagy vesicles (AVs) (induced by autophagy upregulation), and increased expression of the autophagy-proteins LC3, ATG5 and Beclin 1 while p62 was reduced [122,123]. Interestingly, the combination of Abiraterone acetate (AA) and the autophagy inhibitor 3-MA greatly decreased the number of AVs. Inhibition of autophagy impaired cell viability, increased apoptosis, and induced G2/M cell cycle arrest [122,123].

(AA) increased autophagy in LNCaP cells as demonstrated by the upregulation of ATG5 and LC3 and the accumulation of autophagosomes [123]. Cells treated with the autophagy inhibitor 3-MA, or a combination of AA with 3-MA show lower expression of both ATG5 and Beclin 1, which is associated with a reduction of LC3-I and LC3-II [123]. Upregulation of autophagy induces resistance to AA and survival of LNCaP cells and AA treatment in combination with 3-MA increases apoptosis [123].

### Limitations and perspectives

Several studies highlight that autophagy represents a pivotal process in cancer. Here, we have reported many studies in which autophagy is triggered by targeted therapy and results in drug resistance. Consequently, autophagy inhibitors, in most cases, revert the resistance and increase drugs effects *in vitro* and *in vivo*. However, it is questionable that different targeted therapy blocking different pathways in several cancer types will end up in the activation of a similar response to promote drug resistance. To address this issue, we have summarized the most relevant targeted therapies associated pathways in Fig. 1. It is to be noted that almost all targeted therapies interfere directly or indirectly with tyrosine kinases that have the MEK-ERK signaling pathway downstream. MEK-ERK pathway inhibition leads to the activation of LKB1 → AMPK → ULK1 signaling axis, a key regulator of

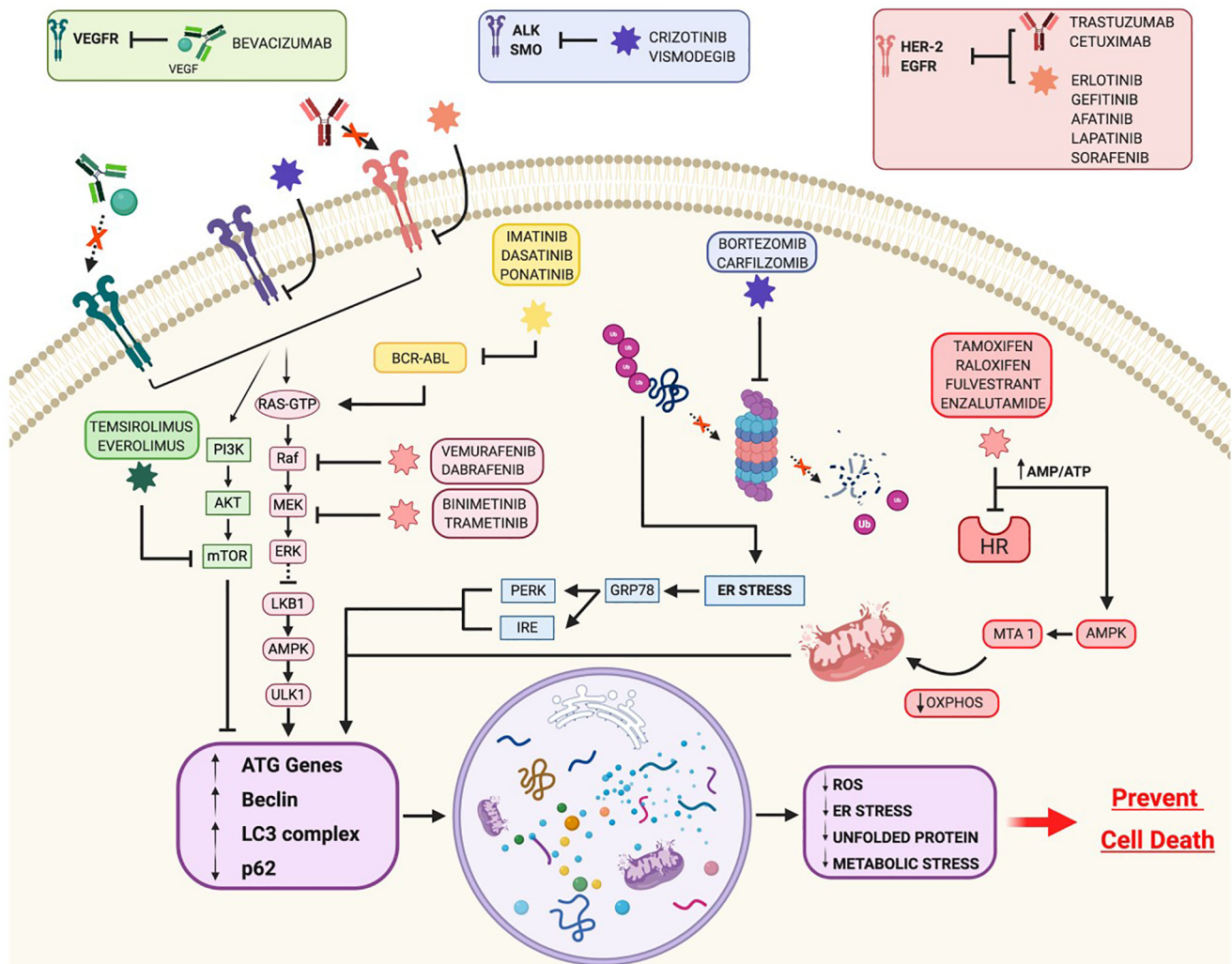
autophagy [111,124]. In addition to this, autophagy can be triggered by several mechanisms associated with targeted therapy such as activation of Beclin 1 through class III PI3K, induction of oxidative and endoplasmic reticulum stress, alteration of AKT-mTOR pathway. Similarly, there are several mechanisms by which autophagy can contribute to drug resistance and survival. For instance, autophagy contributes to cell homeostasis by eliminating damaged organelles such as mitochondria and ER, and protein aggregates. Thanks to this action, autophagy can mitigate metabolic, oxidative and endoplasmic reticulum stresses [125,126]. Several studies report that these cellular stresses contribute to cell death following targeted therapies. For example, vemurafenib and bortezomib mediate cell death through ER stress in melanoma and pancreatic cancer [127,128] as well as apatinib in colorectal [65]. Similarly, erlotinib induces cell death through metabolic oxidative stress in head and neck squamous carcinoma [129]. In addition, autophagy can be involved in target recycling thus reducing the efficacy of targeted therapies [25]. Besides autophagy, many other resistance mechanisms have been identified and divided in three main categories: (1) alterations of the drug target, (2) alterations in upstream and downstream effectors resulting in pathway reactivation and (3) bypass mechanisms [130]. All these mechanisms require deep alteration at genetic or epigenetic level, which develop over time under selective pressure. On the contrary, autophagy is a generic response that is activated by a variety of cellular stress in a short time (within minutes to hours). Moreover, it does not require deep genetic or epigenetic alteration or selective pressure. Based on this, autophagy can be defined as an early and unique mechanism by which cancer cell counteracts the effect of targeted-therapy-induced stress. Indeed, drugs targeting autophagy are being tested in different clinical trials, in combination with standard chemotherapy or targeted therapy. However, there are limitations and concerns that need to be addressed. Autophagy has a dual role which is highly dependent on the specific context. Knockdown of autophagy-related genes increases the incidence of cancer in many tissues and, in certain conditions, it can contribute to cell death by a process named autosis. Moreover, autophagy is necessary for physiological processes in many cells such as immune system regulation, metabolism and senescence [131,132]. Indeed, autophagy inhibitors such as CQ and HCQ, which have been largely used to treat malaria and autoimmune disease, are not free of side effects that range from skin rash to muscle weakness up to gastrointestinal and neurological disorders, and irreversible retinopathy. The severity of side effects becomes more important in long term treatments. In addition, CQ might exacerbate chemotherapy-related injuries in organs such as kidney, brain, heart and hematopoietic cells [133]. One additional important limitation concerns drugs specificity as both CQ and HCQ do not specifically inhibit autophagy. They rather accumulate into acidic cellular compartments and interfere with lysosomal function thus affecting autophagy as well as other cellular functions. For these reasons, it would be ideal to have a specific marker to identify those patients in which autophagy plays a major role and maximize treatments effect. Unfortunately, this marker is not available yet as monitoring autophagy *in vivo*, especially in humans, is particularly challenging.

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### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



**Fig. 1.** Simplified schematic summary of the different mechanisms by which targeted therapies can induce autophagy. Several targeted therapy drugs impact, directly or indirectly, on the MEK-ERK signaling and induce autophagy by activating the LKB1 → AMPK → ULK1 signaling axis, a key regulator of autophagy. Many others impact on AKT-mTOR signaling which is the master autophagy regulator pathway. Proteasome inhibitors causes the accumulation of unfolded protein, which induce ER stress drive autophagy (ER-phagy). Hormones receptors blockade affect mitochondrial function, which induces mitochondria driven autophagy (mitophagy). Activation of autophagy machinery promote cell survival and drug resistance by mitigating cellular stress such as ER, oxidative and metabolic stresses. This must be considered a simplified schematic as many of this mechanisms can be activated contemporarily in different context, e.g. vemurafenib is a Raf inhibitor but it can also induce cell death through ER stress.

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