New Perspectives in Cancer Therapy: The Biotin-Antitumor Molecule Conjugates

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Abstract

Chemotherapy is still the first-line treatment of cancer, even if drugs currently used in therapy generally possess high toxicity and poor selectivity. In the last two decades several efforts have been made to overcome these drawbacks by specifically carrying anticancer drugs to the tumors. Among the different approaches, the so-called vitamin-mediated drug targeting has recently emerged as a novel and valuable strategy. Indeed, the linkage of cytotoxic drugs to selected vitamins, leading to vitamin-drug conjugates, would result in specifically delivering great amounts of the targeted drug at high doses to cancer cells. Among vitamins, biotin seems to be the most promising targeting agent. The aim of this review is to get an overview on recent success in the conjugation of biotin with molecules endowed with anticancer properties.

Keywords: Anticancer drugs; Biotin; Doxorubicin; Drug targeting; Gemcitabine; Taxol

Introduction

Chemotherapy is still the first-line treatment of cancer, even if the drugs currently used in therapy generally possess high toxicity and poor selectivity. Drugs commonly used in cancer therapy are characterized by different mechanisms of action i.e. i) toxicity to specific cancer cells, ii) anti-proliferative activity or iii) capability of modifying the cell cycle at specific phases [1-5]. As a direct consequence of the cellular activity of anti-cancer drugs, in particular with respect to rapidly proliferating and dividing cells, they show low selectivity towards not-cancerous cells like red blood cells, gut epithelia, bone marrow or hair follicles [6]. On the other side, due to the slow proliferation typical of certain tumors, several anticancer drugs used so far result ineffective against such tumors, thus leading to the need of high dose therapies to limit the cancer growing. These high doses could destroy part of the cancer cells but also result in a hard damage to the adjacent normal-proliferating cells. Due to these drawbacks, the cancer therapy has to be discontinued and sometimes stopped before the tumor mass has been reduced or eliminated [7,8]. Thus, reaching a real selectivity of anti-cancer drugs is a milestone and still a challenge in cancer research. To this aim, different approaches could be applied. One of the most common consists in providing the drug with a suitable carrier. The polymeric drug carriers emerged as the most effective ones because of their versatility of use as well as their straightforward chemical modification [9-17]. These systems usually bring to a passive drug targeting due to their ability to accumulate in a specific organ as a result of their route of elimination or for particular organotropism. A more specific drug targeting could be attained by providing the carrier with specific targeting agents, such as antibodies, vitamins, magnetic particles, hormones or peptides [18-24]. Another widely applied approach for drug targeting is the direct linking of the targeting molecule to the drug to form a new chemical entity pharmacologically active per se or a prodrug [7,25-27]. In this context, the so-called vitamin-mediated drug targeting has recently emerged as a novel concept in specifically carrying anticancer drugs to the tumors [7,28-31]. As known, for their survival living cells need to consume vitamins during their life cycle. This is particularly true for those cells that rapidly divide, such as cancer cells. Indeed, the intense metabolic activity of cancer cells arises from their fast growth and is accompanied by a strong use of essential vitamins; consequently the receptors involved in vitamin internalization are overexpressed on the cell surface. This concept is essential from a therapeutic point of view. In fact, it has been argued that the linkage of cytotoxic drug to selected vitamins, leading to vitamin-drug conjugates, would result in specifically delivering great amounts of the targeted drug at high doses to cancer cells. Among vitamins, biotin seems to be the most promising targeting agent.

Keywords: Anticancer drugs; Biotin; Doxorubicin; Drug targeting; Gemcitabine; Taxol

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Among these agents, Paclitaxel is a natural highly oxygenated diterpenoid that was first isolated in 1971 from the stem bark of the western yew, Taxus brevifolia. It is widely used to treat a variety of solid tumors such as breast, ovarian, non-small cell lung, head and neck cancers [47,48]. Since Paclitaxel was discovered, its structure has been extensively studied and modified yielding the so called taxoids, a class of proven anticancer drugs which promote microtubule assembly and suppress microtubule dynamics, thus causing the block of mitotic activity and subsequent cellular apoptosis [3,5].

In 2010, Chen et al., applied what they called “an efficient mechanism-based tumor-targeting drug delivery system, based on tumor-specific vitamin-receptor mediated endocytosis...”. The Authors prepared a biotin conjugates with one of the new-generation taxoids, SBT-1214 [40]. The approach of this work is clear: to use the biotin- SBT-1214 conjugate 1 (Figure 1), which is characterized by an intracellularly labile disulfide linkage, to target the cancer cell by exploiting the overexpression of biotin receptor on the tumor cell surface.

In order to follow the entire process involved in the tumor targeting of the conjugate, the Authors synthesized three fluorescent biotin conjugates (Figure 2): i) the biotin-fluorescein conjugate 2, to observe the receptor-mediated endocytosis by tracking the fluorescent biotin in its route, ii) the biotin-coumarin conjugate 3, as a fluorogenic probe to evaluate the intracellular degradation of the disulfide linkage between the linker and coumarin, which becomes fluorescent only when it is released as a free molecule via disulfide cleavage of the spacer and iii) the biotin- SBT-1214 -fluorescein conjugate 4, to validate the whole internalization by receptor-mediated endocytosis and drug release processes, wherein the released fluorescent taxoid should bind to microtubules in the cancer cells.

In details, conjugates 2, 3 and 4 have been tested on L1210FR murine leukemia cell line, which overexpress receptors for biotin on their cell surface. Firstly, the Authors proved the internalization of the biotin-fluorescein conjugate 2 into the leukemia cells, by evaluating the intracellular fluorescence after incubation with the probe. Furthermore, they confirmed that the internalization was receptor-mediated by pre-incubation of the same cells with an excess of free biotin. They found that in these conditions the fluorescence of the biotin-fluorescein conjugate 2 decreased about 4.5 times, thus confirming that the biotin-fluorescein internalization is receptor-mediated. Secondly, the Authors confirmed the effectiveness of the fluorogenic biotin- coumarin conjugate 3 by incubating the chosen cell line with conjugate 3. Differently from...
conjugate 2, the intracellular fluorescence for conjugate 3 could be only evidenced after reductive cleavage of the spacer. Due to the visualized intracellular fluorescence, this study clearly demonstrated that the intracellular release of coumarin via cleavage of the disulfide linkage by GSH followed by thiolactonization took place as designed. Successively, they tested the biotin-SBT-1214-fluorescein conjugate 4. These results confirmed the internalization of the conjugate and also clearly proved that the released fluorescent taxoid binds to the microtubules. A cross-confirmation of the previous data has been performed by testing conjugate 4 using two more cell lines, L1210 murine leukemia cell line and WI38 noncancerous human lung fibroblast cell line, which do not overexpress receptors for biotin on their cell surfaces. This experiment resulted in a much stronger (about 12-13 times) fluorescence in L1210FR cells (with biotin receptors overexpressed) as compared to that in L1210 or WI38 cells, so confirming the biotin-mediated drug targeting. Finally, the Authors evaluated the cytotoxicity of the compound 1 against L1210FR, L1210 and WI38 cell lines by using the MTT assays. The conjugate 1 resulted high cytotoxic against L1210FR (IC\textsubscript{50} 8.8 nM), while the cytotoxicity against L1210 (IC\textsubscript{50} 522 nM) and WI38 (IC\textsubscript{50} 570 nM) cell lines were 59 times and 65 times the cytotoxicity against L1210 (IC\textsubscript{50} 522 nM), which demonstrates that these systems could differentiate cancer cells from normal ones so reducing the side effects related to the use of cytotoxic drugs. These results are of paramount importance in the field of biotin targeted drugs because clearly demonstrated that: i) the biotin-drug conjugates are preferentially internalized into cancer cells, ii) the toxicity against normal cell is significantly reduced, and iii) the intracellular cleavage of the employed spacer allows a better systemic stability and a lower interaction with non-cancerous cells.

**Biotin conjugated to doxorubicin**

The antibiotic doxorubicin is extensively used against different human cancers, such as breast cancer, soft tissue sarcomas, and Hodgkin’s and non-Hodgkin’s lymphomas. The anticancer activity of doxorubicin has been addressed to several mechanisms of action: i) inhibition of DNA synthesis in the tumor cell, ii) generation of free radicals, iii) DNA adduct formation and DNA cross-linking, iv) interference with DNA strand separation and DNA helicase, v) interaction with cell membranes, vi) induction of DNA damage through interference with topoisomerase II, vii) induction of apoptosis and viii) growth arrest of tumor cells [49]. Nevertheless, the clinical use of doxorubicin is affected by several harmful side effects, among them, the cardiotoxicity is the most important one, leading to cardiomyopathy and congestive heart failure. Indeed, doxorubicin is known to cause cardiotoxicity through multiple routes, including the build-up of reactive oxygen species and disruption of the calcium homeostasis in cardiac myocytes. Several approaches have been proposed to limit its cardiotoxic effects, i.e. incorporation of the drug inside liposomes, formation of prodrugs proteolytically activated in the tumor cells, or the formation of polymeric prodrugs bearing specific drug-targeting moieties. Although these approaches are valuable, they are still not resolving the drawbacks connected to doxorubicin side effects [50]. Aiming at limiting the adverse side effects of doxorubicin, in 2010 Ibsen S. et al. designed and synthesized the biotin-doxorubicin conjugate 5 (Figure 3), in which the amine group of doxorubicin was derivatized with a photocleavable biotinylated spacer [51].

They demonstrated that the active drug is released only after the internalization of the conjugates in cancer cells and the subsequent activation of the photocleavable group via exposure to UV at 350 nm, thus minimizing the cytotoxic effects on not-cancerous cells.
good drug candidate to reduce the undesirable systemic side effects of strongly suggest that the biotin-doxorubicin conjugate 5 could be a UV irradiation. Overall, result obtained so far in-situ “activated” by so targeting the conjugate to tumor cells, where the drug could be obtain a system able to spare not-cancer cell from the drug cytotoxicity biotinylated ones [25,53]. Summarizing, this approach allowed to from the human body could be higher than the corresponding not-counterparts of biotinylated molecules been demonstrated that the elimination of biotinylated molecules rate of the freely circulating biotinylated doxorubicin, because it has incorporation of the biotin moiety might help to increase the clearance important consideration that emerges from this study is that the of free doxorubicin, being the IC_{50} value equal to 1.2 µM and 250 µM for doxorubicin and the biotin-doxorubicin conjugate, respectively. As expected, after UV exposure of the treated cells, the IC_{50} values for conjugate 5 resulted comparable to that of free doxorubicin. Another important consideration that emerges from this study is that the incorporation of the biotin moiety might help to increase the clearance rate of the freely circulating biotinylated doxorubicin, because it has been demonstrated that the elimination of biotinylated molecules from the human body could be higher than the corresponding not-biotinylated ones [25,53]. Summarizing, this approach allowed to obtain a system able to spare not-cancer cell from the drug cytotoxicity so targeting the conjugate to tumor cells, where the drug could be “activated” by in-situ UV irradiation. Overall, result obtained so far strongly suggest that the biotin-doxorubicin conjugate 5 could be a good drug candidate to reduce the undesirable systemic side effects of doxorubicin.

Biotin conjugated to gemcitabine

Gemcitabine is an anti-metabolite used to control non-small cell lung, pancreatic, metastatic breast and current ovarian cancers [54,55]. After cellular uptake, gemcitabine is phosphorylated to gemcitabine monophosphate (dFdCMP) which, in turn, is converted to gemcitabine di- and triphosphate (dFdCDP and dFdCTP, respectively) that are the active drug metabolites. The triphosphate analogue of gemcitabine acts i) replacing one cytidine during DNA replication and ii) inhibiting the DNA polymerase [56]. Some characteristic of gemcitabine, i.e. its short plasma half-life (9-13 min in human) due to its rapid renal clearance, and its myelosuppression side effect, contribute to decrease the gemcitabine chemotherapeutic index [57].

In their efforts to overcome the side effects of gemcitabine, in two recent papers Maiti et al. and Bhuniya et al. synthesized two new theranostic anticancer targeted prodrugs of gemcitabine (conjugates 6 and 7, Figure 4), which are characterized by a disulfide cleavable linker containing a fluorescent probe (coumarin for 6 and IR fluorescent BODIPY fluorophore for 7) [55,58]. A theranostic is a special type of Drug Delivery System (DDS) useful for therapeutic and diagnostic applications, which is able to provide not only a specific cellular drug release, but also a real time monitoring of the drug released in tissue [59].

The Authors studied the behavior of 6 and 7 in the presence of glutathione (GSH), which is the most abundant thiol in cells, or dithiothreitol (DTT) and demonstrated that gemcitabine release is due to cleavage of the sulhide bond upon GSH or DTT treatment,
followed by an intramolecular nucleophilic substitution of the thiol at the carbamate moiety. This mechanism of gemcitabine release is supported by further studies carried out in the presence of different biologically relevant analyte containing or not thiol groups, such as cysteine, homocysteine, non-thiol amino acids or metal ions. Results clearly evidenced that conjugates 6 and 7 undergo only a thiol-mediate cleavage, with no significant interference from other molecules present in biological environment. To investigate whether the biotin moiety can guide 6 and 7 to biotin receptor-positive or biotin receptor-negative tumor cells, Authors evaluated the fluorescence by confocal microscopy in A549 (biotin receptor-positive) and WI38 (biotin receptor-negative) cells pre-incubated with 6 and 7. A strong fluorescence intensity was only observed in the A549 cells, thus confirming that biotin acts as targeting agent to cancer cells. Additionally, to investigate the intracellular location of gemcitabine release, Authors performed co-localization experiments using fluorescent endoplasmic reticulum (ER) and lysosome-selective markers. They found that biotin-gemcitabine conjugate 7, containing the near IR BODIPY fluorophore, localized to the ER, while biotin-gemcitabine conjugate 6, containing coumarin, localized to the lysosome, probably by receptor mediated endocytosis. The subsequent thiol-induced disulfide cleavage released gemcitabine which, in turn, diffused to the cell nucleus. Finally, MTT assay performed on A549 cells clearly evidenced a stronger anticancer effect for the biotin conjugates 6 and 7 with respect to their analogues without the biotin moiety, further confirming the biotin-mediated targeting to tumor cells. In summary, also in these studies the conjugation of the biotin moiety, further confirming the biotin-mediated targeting for the biotin conjugates 6 and 7 with respect to their analogues without biotin, are twelve to forty nine times more active against 4T1 cells and P815 cell lines, respectively, than the corresponding mono-biotinylated derivative 12 (Figure 6). Interestingly, the Authors also noticed that the optimal site of attachment of biotin strongly depend on whether or not the 6-amino-caproic acid residue is present as a linker between the ACG scaffold and the biotinyl residue. Particularly, concerning biotin-squamocin conjugates, the preferred site of attachment of biotin is the C-28 hydroxyl group when biotin is directly attached to the scaffold, and become the C-15 hydroxyl group when the linker between biotin and squamocin is present. In the case of biotin-bullatacin conjugates, the optimal site for biotinyl derivatization is the C-15 hydroxyl group in the absence of the linker, which changes to the C-4 and C-24 hydroxyl groups in the presence of the linker. Moreover, regarding the effect of the linker on the biological activity, Authors showed that biotin-ACG conjugates bearing the linker are generally more potent than the analogues which lack such linker, thus proving that the presence of the linking spacer positively affect the anticancer potential of the conjugates. Indeed, the biotin-squamocin conjugate 12 (Figure 6), biotinylated at C-15 and bearing the linker between squamocin and biotin, is almost four and ten times more potent against 4T1 cells and P815 cells, respectively, than the analogue without the linker. Similarly, conjugates 11 and 13 (Figure 6), biotinylated at C-24 and C-4, respectively, and both bearing the linker between bullatacin and biotin, are twelve to forty nine times more active against 4T1 cells and P815 cells, respectively, than the corresponding analogues without the linker. In summary, in this study a broad investigation of the effect of biotin conjugation on the anticancer activity of two ACGs has been described. The results clearly proved that biotin conjugation significantly increases the anticancer potential ACGs, which, in turn, is significantly affected by i) the number of biotinyl residues included in the conjugates, ii) the point of attachment of the biotinyl residue, as well as iii) the presence or not of a spacer between ACG and biotin.

Concerning the influence of the number of biotinyl residues on the cytotoxic activity, the Authors found that the addition of a second biotinyl residue does not generally result in further improvement of the potency of the biotin-ACG conjugate, with the only exception of the already mentioned biotin-squamocin conjugate 10. Indeed, this conjugate, which is characterized by two biotinyl moieties, resulted up to three times more potent and two times more selective than the corresponding mono-biotinylated derivative 12 (Figure 6). Interestingly, the Authors also noticed that the optimal site of attachment of biotin strongly depend on whether or not the 6-amino-caproic acid residue is present as a linker between the ACG scaffold and the biotinyl residue. Particularly, concerning biotin-squamocin conjugates, the preferred site of attachment of biotin is the C-28 hydroxyl group when biotin is directly attached to the scaffold, and become the C-15 hydroxyl group when the linker between biotin and squamocin is present. In the case of biotin-bullatacin conjugates, the optimal site for biotinyl derivatization is the C-15 hydroxyl group in the absence of the linker, which changes to the C-4 and C-24 hydroxyl groups in the presence of the linker. Moreover, regarding the effect of the linker on the biological activity, Authors showed that biotin-ACG conjugates bearing the linker are generally more potent than the analogues which lack such linker, thus proving that the presence of the linking spacer positively affect the anticancer potential of the conjugates. Indeed, the biotin-squamocin conjugate 12 (Figure 6), biotinylated at C-15 and bearing the linker between squamocin and biotin, is almost four and ten times more potent against 4T1 cells and P815 cells, respectively, than the analogue without the linker. Similarly, conjugates 11 and 13 (Figure 6), biotinylated at C-24 and C-4, respectively, and both bearing the linker between bullatacin and biotin, are twelve to forty nine times more active against 4T1 cells and P815 cells, respectively, than the corresponding analogues without the linker. In summary, in this study a broad investigation of the effect of biotin conjugation on the anticancer activity of two ACGs has been described. The results clearly proved that biotin conjugation significantly increases the anticancer potential ACGs, which, in turn, is significantly affected by i) the number of biotinyl residues included in the conjugates, ii) the point of attachment of the biotinyl residue, as well as iii) the presence or not of a spacer between ACG and biotin.
Biotinylation of Protein with Antitumor Effect

Biotin conjugated to p53 protein

p53 is a transcription factor involved in various cellular functions, such as cell-cycle regulation, initiation of apoptotic cell death and DNA repair. Mutated or otherwise deactivated p53 is observed in the majority of human cancers [65]. Several mechanisms, i.e. mutations in p53 DNA binding domain and enhanced proteasomal degradation upon ubiquitination, are responsible for p53 inactivation. Due to its vital functions, p53 has attracted a great attention, and several approaches have been pursued to deliver p53 into tumor cells [66]. In this context, in 2013 Fahrer et al. demonstrated that biotinylation of p53 represents a successful strategy to target and deliver the protein to cancer cells [67]. In this study the Authors take advantage of the already developed C2-streptavidin transporter [68,69] to introduce the biotin conjugation to p53 could be used for wide number of labile proteins or peptides of pharmaceutical interest.

Conclusions

This review gives a highlight on recent progresses on the so-called biotin-mediated drug targeting of molecules endowed with anticancer properties. Particularly, the review has been organized in three different sections in which we have examined recent success in the conjugation of biotin with i) anticancer drugs commonly used in cancer therapy (toxoids, doxorubicin and gemcitabine) or their derivatives, as well as ii) anticancer drug candidates or iii) protein with antitumor effect, furnishing biotin conjugates able to preferentially deliver the anticancer molecules to cancer cells.

In summary, from the analysis of the literature on this topic clearly emerged that the conjugation of biotin with anticancer molecules represents an attractive and highly innovative approach to improve efficiency and efficacy and reduce cytotoxicity of anti-cancer therapy.

Figure 6: Chemical structure of biotin-squamocin conjugates 10 and 12; chemical structure of biotin-bullatacin conjugates 11 and 13.
Although only few targeted drugs have been developed so far, this area is in constant growth and we strongly believe that this approach could give an added value to cancer therapy.

References


Figure 7: Schematic representation of the cellular internalization of a biotin-p53 conjugate mediated by the C2-streptavidin transporter.

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