Advances in the development of hybrid anticancer drugs

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Advances in the development of hybrid anticancer drugs

Sébastien Fortin & Gervais Bérubé

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Introduction: Hybrid anticancer drugs are of great therapeutic interests as they can potentially overcome most of the pharmacokinetic drawbacks encountered when using conventional anticancer drugs. In fact, the future of hybrid anticancer drugs is very bright for the discovery of highly potent and selective molecules that triggers two or more cytotoxic pharmacological mechanisms of action acting in synergy to inhibit cancer tumor growth.

Areas covered: This review represents the most advanced and recent data in the field of hybrid anticancer agents covering mainly the past 5 years of research. It also accounts for other significant reviews already published on the topic of anticancer hybrids. The review showcases the research that is at the leading edge of hybrid anticancer drug discovery. The main areas covered by the present review are: DNA alkylating agent hybrids (e.g., platinum(II), nitrogen mustard, etc.), vitamin-D receptor, agonist-histone deacetylase inhibitors, combi-molecule therapies and other types of hybrid anticancer agents.

Expert opinion: The current development in the field describes strategies that have never been used before for the design of hybrid anticancer drugs. The information currently available and described in this section allows us to identify the main parameters required to design such molecules. It also provides a clear view of the future directions that must be explored for the successful development and discovery of useful hybrid anticancer drugs.

Keywords: anticancer agents, combi-molecules, drug design, drug-targeting, hybrids


1. Introduction

This review presents the most recent advances in the design and development of hybrid anticancer agents. This type of design was comprehensively reviewed in 2009 by Gediya and Njar [1] and, in 2007 by Viegas-Junior et al. [2]. As a rule, the review showcases the most current work in the field. Consequently, molecular structures already described in the previous reviews will not be addressed and only hybrids recently published in the literature will be discussed at the exception of hybrids required to illustrate significant elements of the discussion. Moreover, for sake of clarity and conciseness, only the most promising and potent hybrids will be described. The goal of this review is also to assist and guide the scientific community to design even better hybrid anticancer drugs for the next generation of cancer treatments.

Hybrid drug design is in constant evolution and remains essential for the discovery of innovative and potent anticancer drugs. To that end, several research groups are devising and testing new chemical and biochemical strategies for their development. This review is divided into sections that take into account two main ways by which hybrid anticancer molecules can be designed and prepared: i) merge and blend haptophoric moieties of different drugs and ii) combine two or several entire drugs together. Some hybrids use both design approaches and are therefore difficult to classify in one or the other category.
Merging haptophoric moieties of different drugs is the first strategy that has been used to design new anticancer hybrids. Table 1 shows the parental anticancer drugs and their mechanism of action used for the design of potent hybrids.

2.1 Hybrid anticancer molecules aiming to an identical biological target

The first strategy approach is the synthesis of the merging of two haptophoric groups selected from two drugs exhibiting the same cytotoxic mechanism of action. This design aims to improve activity, selectivity and biopharmaceutical properties (absorption, distribution, metabolism, and excretion properties) of both parental anticancer drugs. Several anticancer hybrids designed following this concept are shown in Figure 1.

The indenoisoquinoline–camptothecin hybrids (23a and b) result from the merging of two topoisomerase I inhibitors: camptothecin (1) and 5,11-diketoindenoisoquinoline (NSC 314622, 2), respectively. The hybrids combine the 2,3-dihydro-1H-pyrrolo[3,4-b]quinoline haptophoric moiety of compound 1 at position 6 and 7 of the isoquinolone moiety of compound 2 [3]. Compounds 23a, b exhibit antiproliferative activity in the micromolar range and possess significant topoiso-merase I inhibitory activity but show lower biological activity than their parental compounds alone.

Nguyen et al. thoroughly reviewed the antitumor activity of psoropermum xanthones and sarcomelicope acridones [4]. Their review also discusses the biological properties of several hybrids such as epoxycrocaridine (24) and pyranoxanthone (25). The latter are merging the haptophore of psorospermum (3) and acronyceine (4), two anticancer drugs targeting DNA. The epoxycrocaridine 24 was prepared by amalgamating the xanthone moiety of compound 4 and the epoxifu-ran of compound 3, whereas pyranoxanthone 25 was designed using the xanthone moiety of compound 3 and the pyran group of compound 4. Compound 24 exhibits antiproliferative activity in the nanomolar range, while compound 25 shows only marginal antiproliferative activities.

Compound 26 is a new Philadelphia chromosome (Bcr-Abl) inhibitor hybrid that has been designed using molecular fragments found in FDA approved imatinib (5), dasatinib (6) and nilotinib (7) [5] namely the pyridine group of compound 5, the thiazol-2-amine and the 4-methyl-N-phenylbenzamide moieties of compounds 6 and 7, respectively. Compound 26 exhibits antiproliferative activity in the nanomolar range, which is in the same order of magnitude as nilotinib on the cancer cell lines assessed. In addition, compound 26 displays similar inhibitory potency on Bcr-Abl kinase than that of nilotinib, arrests the cell cycle progression in G0/G1-phase and induces apoptosis of K562 cancer cells.

Combination of the benzamidyl moiety of MS-275 (8) in the aliphatic chain of trichostatin A (TSA, 9), two histone deacetylase (HDAC) inhibitors (HDACi), lead to the generation of SK-7041 (27) [6]. Compound 27 exhibits antiproliferative activity in the low micromolar range and is fivefold more potent than vorinostat (SAHA, 10) on lung and breast cancer
Table 1. Parental anticancer drugs and their mechanism of action used in the design of merged haptophoric moiety hybrid of different drugs.

<table>
<thead>
<tr>
<th>#</th>
<th>Names</th>
<th>Structures</th>
<th>Main mechanism(s) of action</th>
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<tbody>
<tr>
<td>1</td>
<td>Camptothecin</td>
<td><img src="image" alt="Camptothecin" /></td>
<td>Topoisomerase I inhibitor</td>
</tr>
<tr>
<td>2</td>
<td>5,11-Diketoindenoisoquinoline (NSC 314622)</td>
<td><img src="image" alt="5,11-Diketoindenoisoquinoline" /></td>
<td>Topoisomerase I inhibitor</td>
</tr>
<tr>
<td>3</td>
<td>Psorospermin</td>
<td><img src="image" alt="Psorospermin" /></td>
<td>DNA strand breaks</td>
</tr>
<tr>
<td>4</td>
<td>Acronycine</td>
<td><img src="image" alt="Acronycine" /></td>
<td>DNA alkylation</td>
</tr>
<tr>
<td>5</td>
<td>Imatinib</td>
<td><img src="image" alt="Imatinib" /></td>
<td>TK Bcr-Abl and Src inhibitors</td>
</tr>
<tr>
<td>6</td>
<td>Dasatinib</td>
<td><img src="image" alt="Dasatinib" /></td>
<td>TK Bcr-Abl and Src inhibitors</td>
</tr>
<tr>
<td>7</td>
<td>Nilotinib</td>
<td><img src="image" alt="Nilotinib" /></td>
<td>TK Bcr-Abl inhibitors</td>
</tr>
<tr>
<td>8</td>
<td>MS-275</td>
<td><img src="image" alt="MS-275" /></td>
<td>HDAC inhibitors</td>
</tr>
<tr>
<td>9</td>
<td>Trichostatin A (TSA)</td>
<td><img src="image" alt="Trichostatin A (TSA)" /></td>
<td>HDAC inhibitor</td>
</tr>
<tr>
<td>10</td>
<td>Vorinostat (SAHA)</td>
<td><img src="image" alt="Vorinostat (SAHA)" /></td>
<td>HDAC inhibitor</td>
</tr>
<tr>
<td>11</td>
<td>Discodermolide</td>
<td><img src="image" alt="Discodermolide" /></td>
<td>Microtubule-stabilizing agent</td>
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N.D: Not fully determined.
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<td>12</td>
<td>Dicystatin</td>
<td></td>
<td>Cancer prevention</td>
</tr>
<tr>
<td>13</td>
<td>5-Fluorouracil</td>
<td></td>
<td>Thymidylate synthase inhibitor</td>
</tr>
<tr>
<td>14</td>
<td>Propafenone</td>
<td></td>
<td>Anti-arrhythmic</td>
</tr>
<tr>
<td>15</td>
<td>Resveratrol</td>
<td></td>
<td>Cancer prevention</td>
</tr>
<tr>
<td>16</td>
<td>Coumarin</td>
<td></td>
<td>Anti-arrhythmic</td>
</tr>
<tr>
<td>17</td>
<td>Neo-tanshinlactone</td>
<td></td>
<td>Anti-arrhythmic</td>
</tr>
<tr>
<td>18</td>
<td>Benzodiazepines</td>
<td></td>
<td>Allosteric modulator of GABA~A</td>
</tr>
<tr>
<td>19</td>
<td>1a,25-Vitamin D3 (1,25D)</td>
<td></td>
<td>Vitamin D receptor agonist</td>
</tr>
<tr>
<td>20</td>
<td>3,3-Diarylpentanes (LG190178)</td>
<td></td>
<td>Vitamin D receptor agonist</td>
</tr>
<tr>
<td>21</td>
<td>Bevacizumab</td>
<td></td>
<td>Anti-arrhythmic</td>
</tr>
<tr>
<td>22</td>
<td>Chalcone</td>
<td></td>
<td>Cancer prevention</td>
</tr>
</tbody>
</table>

N.D: Not fully determined.
cell lines. This hybrid also shows time-dependent histone hyperacetylation leading successively to G2-M-phase, G1-phase arrest and ultimately to apoptosis.

In 2008, Florence et al. reviewed the marine anticancer agents such as discodermolide (e.g., compound 11) and dictyostatin (e.g., compound 12) and discussed the preparation and the evaluation of several hybrids deriving from these antimitotics [7]. In recent years, Paterson et al. have synthesized several dictyostatin–discodermolide hybrids exemplified by compounds 28a, b [8,9]. This type of hybrid consists of the addition of an alkene bond and an α-methyl group at positions 15 and 18 of compound 11 on the molecular structure of compound 12. These hybrids are based on the overlapping molecular structure of compound 12 and the semicyclic conformation of compound 11. Compounds 28a, b show antiproliferative activity in the low nanomolar range on several cell lines, which is in the same order of magnitude than compounds 11, 12 and paclitaxel. Dictyostatin–discodermolide hybrids are microtubule-stabilizing agents that do not interact with P-glycoprotein (P-gp) and still highly cytocidal against paclitaxel-resistant cancer cell lines.

2.2 Hybrid anticancer molecules aiming to multiple biological targets

The second strategy used in merge haptophoric moieties of different drugs is to integrate two different drugs that are separately addressing separately two or multiple biological targets. Again, this strategy is used to design new families of drugs to improve the pharmacokinetic and pharmacodynamic properties of the parent components as well as to synergize their mechanisms of action in a single molecular entity structure. This approach seems to disobey to conventional strategies used in medicinal chemistry where the selectivity of a molecule for a specific biological target is the cornerstone for the development of new drugs. However it is in agreement with the logic of using ‘chemotherapeutic cocktails’ in clinic that are combining chemotherapeutic agents exhibiting different mechanisms of action (e.g., 5-fluorouracil, epirubicin, cyclophosphamide for the treatment of breast cancer) that are more effective than the same agents used alone. In addition, that approach was found to prevent chemoresistance. Therefore, polychemotherapeutic approach was translated in recent years into the design of hybrid molecules aiming at several cytocidal targets at once [10]. Consequently, several new anticancer agent hybrids were recently designed using this strategy and are shown in Figure 2.

Multidrug resistance (MDR) is plaguing chemotherapies of numerous cancer tumors via several mechanisms of action including the increase of efflux of drug (e.g., P-gp, MDR-associated protein). To circumvent chemoresistance, potent MDR modulators are required. To that end, 5-fluorouracil (13), a potent thymidylate synthase inhibitor enzyme was linked to propafenone (14) that is an antiarrhythmic drug known also as a potent MDR modulator to generate the uracil-based hybrid molecules (29a, b) [11]. Compounds 29a, b interact with P-gp at 0.5 µM and could be potential candidates for new MDR modulators.

Stilbene–coumarin hybrids (compounds 30a, b) are composed of the phenylethenyl moiety of resveratrol (15), an agent recognized for its cancer prevention properties and the coumarinic ring system (e.g., compounds 16 and 17). The latter family of anticancer agent acts through a variety of mechanisms of action on the cells and are recognized to exhibit potent proapoptotic effects [12]. Compounds 30a, b exhibit
antiproliferative activity in the low micromolar range on cell lines studied. They arrest the cell cycle progression in the G2--M-phase and induce apoptosis.

Benzodiazepines (18) are a family of psychotropic drugs producing sedative, hypnotic and anxiolytic effects including cytostatic and differentiative effects in a variety of transformed cell types [13]. Guandalini et al. used the latter property of benzodiazepines to design new hydroxamate HDACi (compounds 31a, b) [14]. These hybrids are designed by substituting the aromatic ring of HDACis 9 and 10 by the benzodiazepine ring and merging the hydroxamate function (terminal zinc-binding groups) by an ethynyl and an alkyl chain. Compounds 31a, b exhibit antiproliferative activity in the hundreds of nanomolar range in human acute promyelocytic leukemia NB4 cell line and they also induce histone H3/H4 acetylation.

The 1α,25-vitamin D3 (1,25D, 19) plays a pivotal role in controlling calcium homeostasis and has antiproliferative and cancer chemopreventive properties. Moreover, the antiproliferative effects of the combination of 1,25D and HDACi have been confirmed on 1,25D-resistant cancer cells. Therefore, combination of analogs of 1,25D and a variety of terminal zinc-binding groups including hydroxamate present in classic HDACis 9 and 10 (triciferol, 32a) [15] and 2-mercaptoacetamide (compound 32b) [16] to design vitamin D receptor agonist-HDACi hybrids (compounds 32a, b) has been natural. Compounds 32a, b exhibit antiproliferative activity in AT84 squamous carcinoma cells, bind to the vitamin D receptor and act as HDACi, while they do not trigger hypercalcemic effects, which is a deleterious effect induced by 1,25D.

High-throughput screening recently identified non-secosteroidal 3,3-diarylpentane 20 (LG190178) as a new vitamin D receptor agonist and a more easily synthesizable chemical structures with pro-differentiation and antiproliferative activities without triggering hypercalcemia effects. Fisher et al. merged compound 20 and the terminal zinc-binding groups (hydroxamate function) of compounds 9 and 10 to design the non-secosteroidal vitamin D receptor agonist--HDACi hybrids (JF-B01, 33) [17]. Compound 33 shows antiproliferative activity in the micromolar range on both 1,25D-sensitive (SCC25, AT84) and 1,25D-resistant (SCC4) squamous carcinoma cell lines. Moreover, compound 33 acts as full vitamin D receptor agonist and as a HDACi.

The retinoid--chalcone hybrids (34) are composed of the retinoid moiety of bexarotene (21) combined to the chalcone

Figure 2. Molecular structures of anticancer drug hybrids merging haptophoric groups from two drugs acting through different mechanisms of action.
moiety of compound 22, two potent anticancer molecular entities [18]. Compound 34 shows antiproliferative activity in low micromolar range on colon adenocarcinoma HT-29 cell line.

Chalcone (22) has been also used by Sashidhara et al. and fuses with the coumarin ring systems (compounds 16 and 17) to generate new coumarin–chalcone hybrids (35a–c) [19] that showed antiproliferative activity in the micromolar range on KB, C33A, MCF-7, A549 and NIH3T3 cell lines, with a superior activity on a cervical carcinoma C33A cell line.

3. Combination of two or several entire drugs (combi-molecules)

The amalgamation of two or several entire drugs in the same molecular structure, also termed combi-molecule, is the second approach used in designing new anticancer hybrids. Several anticancer drugs used for this application and their respective mechanisms of action are described in Tables 1 and 2.

3.1 Combi-molecules with the same mechanism of action

The first strategy to design new anticancer hybrids is the connection of two drugs with the same mechanism of action. The drugs can be composed of different drugs and moieties recognized to have enhanced anticancer properties or composed of the same drug (dimer). Several anticancer hybrids designed following this concept are shown in Figure 3A (different drugs hybrids) and B (dimer hybrids).

It is known that antitumor activity of anthracycline antibiotics such as doxorubicin (36a) and daunorubicin (36b) is strongly dependent on the presence of the daunosamine (aminocarbohydrate) moiety. Bednarek et al. used that observation to improve the properties of indolo[2,3-b]quinolones (e.g., compound 37) which are analog of neocryptolepine DNA topoisomerase II inhibitors. They have linked compound 37 to aminoglycoside to produce new indolo[2,3-b]quinoline hybrid (67) that are describe as a new family of potent anticancer drugs [20].

Kumar et al. designed (tetrahydro-β-carboline)-1,3,5-triazole hybrids (compounds 68a, b) connecting tetrahydro-β-carboline (38) and triazine (39), two molecular structure showing potent antiproliferative activities [21]. Compounds 68a, b show antiproliferative activity in the micromolar range on several cancer cell lines and arrest the cell cycle progression in G0/G1-phase.

Triazine (39) has also been connected at position 2, 4 and 6 of the 1-(2-chloroethyl)piperazine moiety which bears a 2-chloroethylamino group raising similitudes with nitrogen mustards (40–42) to give compound 69 [22] that exhibits antiproliferative activity in micromolar range on MCF-7 cells and forms DNA crosslinks and induces apoptosis and necrosis.

Pyrrolo[2,1-c][1,4]benzodiazepines (PBD, 43) are natural antitumor antibiotics known for their cytotoxic and antitumor effects through DNA alkylation and nucleic acid synthesis inhibition. These compounds were reviewed by Gerratana in 2012 [23]. In the literature, several manuscripts reported researches that incorporate an indole moiety in a synthetic anticancer agent showing potent cytotoxicity. Wang et al. have also prepared the PBD-indole hybrids such as compound 70 [24] that displays antiproliferative activity in the nanomolar range, induces apoptosis in A2058 cells, forms stable complexes, binds to DNA and exhibits in vivo antitumor activity in the hollow fiber assay.

The 7-substituted-benzopyran-2-ones-heterocyclic hybrids (e.g., compound 71) were prepared by merging the pyrazolin-5-one heterocyclic ring to a coumarin moiety (compounds 16 and 17) using an acetoxy linker in the aim to mimic geiparvarin (44), a coumarinic analog showing potent antiproliferative activity on various cancer cell lines [25]. Compound 71 displays median antiproliferative activity in the low micromolar range when tested using the National Cancer Institute (NCI) anticancer cell line panel.

Macrosphelide–epothilone hybrids (e.g., MSt-2, 72) are the results of a combination of the 2-methyl-4-(prop-1-en-1-yl) thiazole present in the epothilone (45) and macrosphelide A (46). Compound 72 displays antiproliferative potency on human colon carcinoma (HCT116) and human gastric cancer (AGS) cells, while it shows no effects on human normal dermal fibroblast [26]. It also induces the formation of reactive oxygen species, activation of Jun N-terminal kinase and apoptosis in human lymphoma (U937) [27].

Isatin (47) is an anticancer agent showing high affinity to tyrosine, cyclin-dependent kinases and carbonic anhydrase isozymes. Moreover, diazoles (pyrazoles and pyrazolines) are privileged structures in the design of new anticancer agents. In this context, Havrylyuk et al. have designed and prepared isatin–pyrazoline hybrids (compound 73) [28] that exhibit an antiproliferative activity in the micromolar range and a selectivity index at the GI50 level of 15 toward leukemia subpanel tumor cell lines.

1H-1,2,3-triazole tethered C-5 substituted uracil-isatin conjugates (compounds 74a, b) are another class of anticancer hybrids designed by connecting isatin, uracil and 1,2,3-triazole, three scaffolds considered as privileged structures in anti-neoplasics discovery [29]. Compounds 74a, b exhibit GI50 of 18.21 and 13.90 μM, respectively, on DU145 cell line, while they are inactive on MCF-7 cells.

Singh et al. have also used isatin and 1,2,3-triazole to design new 1H-1,2,3-triazole tethered isatin hybrids (compounds 75a, b) [30]. Compounds 75a, b are the most active compounds of the series prepared and show antiproliferative in the nanomolar range on A549, PC-3 and THP-1 cell lines, whereas they are inactive on Caco-2 cells.

The 3,5-diaryl isoxazoline-linked 2,3-dihydroquinazolino-none hybrids (compound 76) were designed by connecting a five-membered heterocycle analog of combretastatin-A4.

Advances in the development of hybrid anticancer drugs
Table 2. Parental anticancer drugs and their mechanism of action used in the design of combi-molecules.

<table>
<thead>
<tr>
<th>#</th>
<th>Names</th>
<th>Structures</th>
<th>Main mechanism(s) of action</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>a: Doxorubicin: R = OH</td>
<td></td>
<td>DNA intercalation, topoisomerase II inhibitor and generation of iron-mediated free oxygen radicals damaging DNA and cell membranes</td>
</tr>
<tr>
<td></td>
<td>b: Daunorubicin: R = H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Indolo[2,3-b]quinoline</td>
<td></td>
<td>DNA intercalation and topoisomerase II inhibitor</td>
</tr>
<tr>
<td>38</td>
<td>Tetrahydro-β-carboline</td>
<td></td>
<td>DNA intercalation, CDK, topoisomerase I and/or II and monoamine oxidase inhibitor</td>
</tr>
<tr>
<td>39</td>
<td>1,3,5-Triazine</td>
<td></td>
<td>N.D.</td>
</tr>
<tr>
<td>40</td>
<td>Mechlorethamine</td>
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<td>DNA alkylation</td>
</tr>
<tr>
<td>41</td>
<td>Chlorambucil</td>
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<td>DNA alkylation</td>
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<td>42</td>
<td>Melphalan</td>
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<td>DNA alkylation</td>
</tr>
<tr>
<td>43</td>
<td>PBDs</td>
<td></td>
<td>DNA alkylation</td>
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<tr>
<td>44</td>
<td>Coumarin (Geiparvarin)</td>
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<td>45</td>
<td>Epothilone A: R = H</td>
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<td>Microtubule-stabilizing agent</td>
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<tr>
<td></td>
<td>Epothilone B: R = CH₃</td>
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<td></td>
</tr>
<tr>
<td>46</td>
<td>Macrosphelide A</td>
<td></td>
<td>Cell-cell adhesion inhibitor</td>
</tr>
<tr>
<td>47</td>
<td>1H-Indole-2,3-dione (Isatin)</td>
<td></td>
<td>TK, cyclin-dependent kinases and carbonic anhydrase isozyme inhibitor</td>
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N.D.: Not fully determined.
Table 2. Parental anticancer drugs and their mechanism of action used in the design of combi-molecules (continued).

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<td>48</td>
<td>Diaryl-substituted isoxazoline analog of CA-4</td>
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<tr>
<td>49</td>
<td>DHQZ</td>
<td><img src="image2" alt="Structure" /></td>
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<td>Artemisinin</td>
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<td>Gefitinib</td>
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<td>Carmustine (BCNU)</td>
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<td>Oxaliplatin</td>
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<td>57</td>
<td>Acridine</td>
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<td>58</td>
<td>β-Lactam</td>
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<td>59</td>
<td>Pyrene derivatives</td>
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<td>DNA intercalation</td>
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N.D.: Not fully determined.
namely diaryl-substituted isoxazoline derivatives (48) and 2,3-dihydro-2-aryl-4-quinazolinones (e.g., DHQZ, 49) [31]. Compound 76 shows antiproliferative activity in the micromolar range, arrests the cell cycle progression in G2-M-phase, inhibits cyclin B1 and CDK1 and disrupts the cytoskeleton.

Another approach to design anticancer hybrids is the formation of homodimers of anticancer drugs. This strategy is also used to improve biopharmaceutical properties such as low solubility or short plasma half-life of drugs such as artemisinin (50). To overcome those limitations, artemisinin–guanidine hybrids (compounds 77a, b) were designed by connecting two molecules of compound 50 on a guanidine water-soluble backbone [32]. Compounds 77a, b show antiproliferative activity in the 10 nM range on HT-29 cell line.

Likewise, compounds 78a, b are dimers of testosterone and have been designed to act as an 'bidentate' antiandrogen that simultaneously binds to two androgen receptors, resulting in the disruption of the androgen receptor signaling pathway [33]. The dimers were linked together either by a trans or a cis but-2-enyl tether chain. The cis dimer (cis-78b) was more active than the trans counterpart (trans-78b). Compound cis-78b exhibits antiproliferative activity in the micromolar range on prostate LNCaP and PC3 cell lines and is slightly more active than cyproterone acetate, a known antiandrogen used in clinics. However, no selectivity on androgen-dependent prostate cancer cells was observed for these dimers.

### 3.2 Combi-molecules with different mechanisms of action

The combi-molecules were developed with the aim to exploit multi-biological targets. It is one of the most promising approaches to design highly potent, effective and useful therapeutic hybrids. Tumors cells possess numerous proteins, enzymes, signaling pathways or other biological entities to bypass, overcome the mechanisms of action of anticancer drugs.

#### Table 2. Parental anticancer drugs and their mechanism of action used in the design of combi-molecules (continued).

<table>
<thead>
<tr>
<th>#</th>
<th>Names</th>
<th>Structures</th>
<th>Main mechanism(s) of action</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>Acridone</td>
<td><img src="image" alt="Acridone structure" /></td>
<td>DNA intercalation</td>
</tr>
<tr>
<td>61</td>
<td>Homo-azasteroids</td>
<td><img src="image" alt="Homo-azasteroids structure" /></td>
<td>N.D.</td>
</tr>
<tr>
<td>62</td>
<td>Fluorodeoxyglucose ((^{18}\text{F}))</td>
<td><img src="image" alt="Fluorodeoxyglucose structure" /></td>
<td>Distributed in high-glucose-consuming cells</td>
</tr>
<tr>
<td>63</td>
<td>Etoposide</td>
<td><img src="image" alt="Etoposide structure" /></td>
<td>Topoisomerase II inhibitor</td>
</tr>
<tr>
<td>64</td>
<td>Aziridine</td>
<td><img src="image" alt="Aziridine structure" /></td>
<td>N.D.</td>
</tr>
<tr>
<td>65</td>
<td>Nitroxyl compounds (e.g., PROXYL)</td>
<td><img src="image" alt="Nitroxyl compounds structure" /></td>
<td>Accumulation in melanomas</td>
</tr>
<tr>
<td>66</td>
<td>4-Iodobenzamide (BZA)</td>
<td><img src="image" alt="4-Iodobenzamide structure" /></td>
<td>High affinity for melanin</td>
</tr>
</tbody>
</table>

N.D.: Not fully determined.
Figure 3. A. Molecular structures of combi-molecules with the same mechanism of action. B. Molecular structures of combi-molecules with the same mechanism of action (dimer).
agents. These protective molecules and salvation mechanisms abrogate the antiproliferative activity and the induction of apoptosis, normally triggered by anticancer agents, and often induce chemoresistance of the tumor cancer cells. Consequently, that concept aims to target different unrelated or related mechanisms of action to synergize their efficacy and circumvent the rescue mechanisms employed by tumor cells. Several anticancer hybrids designed according to this concept are shown in Figure 4A and B.

Jean-Claude’s research group have extensively studied the combi-molecules concept by merging the pharmacophore moiety of a gefitinib analog (51), an epidermal growth factor receptor (EGFR) tyrosine kinase (TK) inhibitor, with different alkylating groups to generate combi-molecules designated as TZ-I. Chloroethylnitrosourea (compound 79, JDA58) [34], 2-chloroethylamino, (compound 80, ZR2003) [35,36] and mitozolomide moieties (compound 81, JDF12) [37] were linked with compound 51 together since they are important pharmacophore functions responsible for the anticancer properties of nitrosoureas (e.g., carmustine (BCNU, 52)), nitrogen mustards (compounds 40 - 42) and mitozolomide, respectively. Compounds 79, 80 and 81 exhibit antiproliferative activity in the low micromolar range and potent anti-EGFR activity, as well as potent DNA damaging effects.

The 1,2,3-triazene (53) is a relatively new alkylating group entity and when connected to compound 51 (compounds 82, 83 and 84 corresponding to ZRBa4, ZR4 and ZRS1, respectively), it generates methyl diazine, a powerful DNA methylating and damaging agent [38-41]. The first generation of this type of combi-molecules was physiologically unstable. Compounds 82, 83 and 84 were designed to circumvent the unstable triazene moiety when linked to the quinazoline ring. They exhibit antiproliferative activity in the low micromolar range and show EGFR inhibition and DNA damage effects.

Imatinib (5) is used in clinic to inhibit TK Bcr-Abl in the treatment of several cancers notably the chronic myelogenous leukemia. Jean-Claude’s research group also used a similar approach to design new combi-molecules Bcr-Abl/DNA (compound 85, ZRF1) by connecting the pharmacophore of compound 5 to 1,2,3-triazene (53) [42]. Compound 85 exhibits its antiproliferative activity in the nanomolar range and is slightly more active than imatinib alone. It shows well-balanced activity between strong Abl TK inhibitory activity and high levels of DNA damages.

Platinum complexes such as cisplatin (54), carboplatin (55) and oxaliplatin (56) are members of a class of platinum(II)-containing anticancer drugs and are widely used against various cancer types including ovarian carcinoma, lung, head and neck cancers. This class of anticancer drugs generates reactive platinum species that mainly crosslink DNA and inhibits ATM/ATR reparation pathways of cancer cells. Acridine (57) is another privileged molecular structure that is often used in the design of anticancer agents. Drugs designed using this planar molecular structure is recognized as potent DNA intercalating agents (e.g., amsacrine) or to inhibit topoisomerase (e.g., acridine carboxamide, DACA). The platinum–acridine anticancer agent 86 was prepared by linking the acridine moiety to a platinum(II) complex [43]. Compound 86 exhibits an antiproliferative activity in the low nanomolar range and is ~ 100-fold more efficiently than cisplatin on chemoresistant non-small-cell lung cancer (NCI-H460 and NCI-H522 cell lines). In addition, it arrests the cell cycle in S-phase, produces DNA adducts and displays important inhibition of DNA replication similarly as other known platinum(II) complexes.

The 1,2,3-triazole tethered β-lactam-chalcone heterofunctional hybrids (compounds 87a, b) were prepared using a click chemistry approach to merge the β-lactam 58 and the chalcone 22, two molecular structures recognized as potent antiproliferative agents against various cancer cell lines [44]. Compounds 87a, b show cytotoxic activity in the micromolar range on A-549, THP-1 and Caco-2 cell lines.

Nitric oxide (NO) is an important endogenous signaling mediator involved in a variety of biological processes including vasodilatation and vessel homeostasis. Moreover, evidence show that NO released via metabolic pathways also mediates anticancer activity and may prevent metastasis. Hence, NO donating-chalcone hybrids such as compound 88 were designed by conjugating the NO-releasing properties of nitrate ester (ONO2) moiety of chalcones (22) [45]. Compound 88 exhibits antiproliferative activity in the low micromolar range on NCI anticancer cell line panel. The planar and semi-planar ring system of pyrene (59) and acridone (60) are known to intercalate in DNA and to show potent anticancer activity. Kamal et al. have conjugated both structures with PBD (43) to create new pyrene-linked pyrrolo[2,1-c][1,4]benzodiazepine (compound 89) [46] and C8-linked PBD–acridone (e.g., compounds 90) hybrids [47]. Compounds 89 and 90 exhibit median lethal dose (LC50) in the nanomolar range on NCI anticancer cell line panel and display good DNA-binding property.

3.3 Combi-molecules with the aim to target specific biological tissues

The combi-molecule strategy that aims to vectorize anticancer drugs to target specific tissues is also a promising method to design highly effective, nontoxic and useful hybrids. Unfavorable biopharmaceutical properties such as inadequate biodistribution, low tissue penetration and poor tropism for cancer cells are major limitations that prevent most drugs to reach the cancer tissues freely or to be effective, despite high in vitro potency. This concept addresses the problem by adding to an anticancer drug unable to biodistribute itself into the cancer tissue to be targeted a second molecular fragment that can bioaccumulate into that specific tissue. Vectorized anticancer drugs are divided into three different categories: i) combi-molecule based on the conjugation of steroids to an anticancer drug (Figure 5A), ii) other combi-molecule
targeting specific biological tissue (Figure 5B) and iii) combi-molecule targeting specific biological tissue and carrying a radionuclide (Figure 5C).

Despite that combi-molecules of steroid-anticancer hybrids were thoroughly reviewed in 2012 by Dao and Hanson [48], we found that this subset of hybrids has been in constant evolution in recent years, regularly using new approaches, new combinations of molecules to produce molecular hybrids exhibiting pharmacokinetic and pharmacodynamic properties always closer to those required in clinic clearly justifying their presentation.

Over the years, Bérubé’s research group developed several anticancer hybrids where 17β-estradiol was linked to anticancer agents such as platinum-containing anticancer drugs and anthracyclines. Among all compounds they have prepared and biologically evaluated, compound 91 (VP-128) is one of their most promising hit compound [49]. Compound 91 exhibits antiproliferative activity in the low micromolar range.
Figure 5. A. Molecular structures of combi-molecules based on the conjugation of steroids to an anticancer drug. B. Molecular structures of other combi-molecules targeting specific biological tissue. C. Molecular structures of combi-molecules targeting specific biological tissue and carrying radionuclide $^{125}$I.

94a: M = Cu
94b: M = Ni
94c: M = Pt

97: $R = CO_2CH_3$

98

99

100 F14512

101

102a: X = C
102b: X = N

103 ICF01035

104 ICF01040
and is ~2- to 8-fold more potent than cisplatin on estrogen-dependent and estrogen-independent breast cancer cell lines such as MCF-7 and MDA-MB-231, respectively. Moreover, it shows high affinity toward the estrogen receptor α, RNA and DNA and better tumor regression properties than cisplatin on the MCF-7 human breast cancer tumors mice model [50]. They also studied different platinum(II) complexes of compound 91 by replacing the dichloroplatinum(II) moiety by a cyclcobutane-1,1-dicarboxylateplatinum(II) (carboxplatin moiety, 55) and oxalatoplatinum(II) (oxaliplatin moiety, 56) groups leading to compounds 92 and 93, respectively [51]. Compound 93 shows 3- to 5-fold higher activity than compound 92 that is similar to cisplatin (54) and oxaliplatin (56). Interestingly, despite their closely related structures, compound 93 retains an excellent affinity for the estrogen receptor α, while compound 92 loses it completely.

Progesterone is another essential steroid hormone involved in various biological processes including control of mammary homeostasis (e.g., female menstrual cycle, decrease in the maternal immune response), effect on the nervous system (e.g., affect synaptic functioning and myelination) and effect on several other systems. Adsule et al. prepared isothiocyanate-progesterone metal complexes (compounds 94a – c) by merging isothiocyanate metal complexes to progesterone [52]. Compound 94a, bearing a copper complex, show antiproliferative activity in the low micromolar range on five cell lines, whereas the platinum(II) complex (94c) is 2- to 4-fold less active. The nickel complex (compound 94b) also shows activity in the low micromolar range on breast cancer cell lines (MCF-7 and MDA-MB-231) and is inactive on BT20 and PC3 cancer cells through the inhibition of the Akt signaling pathway.

In the aim to reduce the cardiotoxicity of anthracyclines such as doxorubicin (36a), Bérubé’s research group attempted to conjugate this anticancer agent to position 16α of the estrogen skeleton to generate compound 95 [53]. Compound 95 shows antiproliferative activity in the micromolar range on HT-29 and MCF-7 cell lines and is inactive on M21 and MDA-MB-231 cells and exhibits affinity for the estrogen receptor α in the nanomolar range. However, the antiproliferative activity of this compound is about 100-fold lower than compound 36a, suggesting that the molecular conformation is not optimal to keep the affinity for the estrogen receptor and the cytotoxic activity at the same time.

Trafalis et al. used homo-azasteroids (61), which contain an amide group inside the A or the D ring of steroid scaffold, to link aromatic nitrogen mustards (40 – 42) leading to homoaiza-steroidal alkylating esters such as compound 96, NSC-294859 [54]. Compound 96 shows antiproliferative activity in the micromolar range on malignant melanoma cell lines and induces significant cytostatic and antineoplastic effects on B16 melanoma-bearing mice.

Compound 97 is a hybrid connecting aromatic nitrogen mustards (40 – 42) and tyrosine that was designed to mimic the estradiol nucleus [55]. Compound 97 exhibits antiproliferative activity in the micromolar range on prostate, breast, ovarian and uterine cancer cell lines and is slightly more active than chlorambucil (41).

The 18F-fluorodeoxyglucose (compound 62) is a radiopharmaceutical used for medical imaging based on its accumulation in high-glucose-using cells such as brain, kidney and cancer cells. Fluorodeoxyglucose–chlorambucil hybrid (compound 98) was designed by connecting fluorodeoxyglucose (62) and chlorambucil (41) [50]. Compound 98 shows antiproliferative activity in micromolar range and is ~10-fold more active than chlorambucil (41) on B16F0 and CT-26 cell lines. It arrests the cell cycle progression in G2-phase and was highly active in vivo in the CT-26 colon carcinoma and B16F0 melanoma mice models, with log cell kill values of 1.52 and 1.81, respectively.

The design of the quaternary ammonium–melphalan hybrid (compound 99) is based on the high affinity of positively charged quaternary ammonium function for proteoglycans, a component of the chondrogenic extracellular matrix of cartilages that is designed to selectively transport melphalan (42) to cartilage tumor tissues [57]. Compound 99 shows antiproliferative activity in the micromolar range on Saos-2 human osteosarcoma and HEMCSS human chondrosarcoma cell lines, while it is inactive against chondrocytes and M4Beu human melanoma cell lines. It arrests the cell cycle progression in S-phase and it is well tolerated in animals. Compound 99 also inhibits tumor cell growth in vivo in orthotopic model of primary Swarm rat chondrosarcoma.

On one hand, etoposide (63) is a potent semi-synthetic topoisomerase II inhibitor that is derived from podophyllotoxin. On the other hand, the polyamines transport system is frequently expressed in cancer cells. The polyamine- etoposide hybrid 100 (F14512) was designed by replacing the C4 glycosidic moiety of etoposide by a sperminyl chain with the aim to exploit the polyamines transport system to favor its accumulation into the cancer cells [58]. Compound 100 displays antiproliferative activity on a large panel of tumor cell lines and is more active than compound 63 [59,60]. Moreover, compound 100 is more active on cells expressing polyamines transport system and induces cell death by non-apoptotic and senescence-type pathways.

Aziridine (64) is another privileged cytocidal molecular structure found in mitomycin C and thiota and exhibits interesting anticancer properties. Nitrosyl–aziridine hybrid (compound 101) was designed by linking the aziridinyl to nitroxy moiety (compound 65), a stable radical species recognized for its selective accumulation in mice melanotic melanomas [61]. Despite that the authors claimed that the cytotoxicity of this hybrid is not observed, no data are shown to support this statement.

The 4-iodobenzamide (BZA, 66) is a family of anticancer agents that interacts with melanin and shows specific affinity primary and metastasis malignant melanoma tumors. Unit 484 at the INSERM in Clermont-Ferrand (France) has developed several anticancer hybrids that target malignant...
melanoma tumors (compounds 102–104) by connecting analogs of compound 66 to iodine-125 (125I-66). The 125I emits Auger electron that causes double-strand breaks in DNA and has a half-life around 59 days and its high-energy emission results in tissue low penetration (nm). Consequently, this radionuclide must be located within the cancer cells for radiotherapeutic effectiveness and suggests low toxicity for the surrounding healthy tissues. Commercial availability, easy labeling and good physical properties select 125I as a promising radionuclide therapy.

Several poly cyclic heteroaromatic compounds such as chloroquine and acridine orange have been previously shown to bind strongly to melanin. Compounds 102a,b were designed by connecting molecular structure of compound 66 merged with heteroaromatic molecular structure and 125I [62]. Compounds 102a,b bind to melanin, exhibit specific affinity for melanoma tumors in mice bearing melanoma tumors and show significantly higher tumoral uptakes than 125I-66 72 h after administration.

Acridone–radionuclide (ICF01035, 103) and acridine–radionuclide hybrids (ICF01040, 104) were designed by connecting acridone (60) and acridine (57) to 125I [63,64]. Acridone (60) and acridine (57) are known to intercalate into DNA strains and to show potent anticancer activity. Moreover, some acridines and acridones such as DACA (NSC 601316) bearing a basic side chain similar to BZA (66) bind strongly to synthetic melanins and show antiproliferative activity on melanoma cell lines and exhibit antitumor activity on tumor xenografts in mice. Consequently, this design appears suitable for application in vectorized radionuclide therapy. Compounds 103 and 104 bind to melanin, and biodistribution studies on B16F0 murine melanoma tumor-bearing mice show specific, high and sustained in vivo tumor concentrations which is > 10-fold longer than 125I-66.

4. Conclusion

This review shows the various fashions by which a hybrid anticancer agent can be designed. We classified the hybrids into several categories according to their construct, same or different drugs and their intended targets (or mechanism(s) of action) being single, multiple or simply as vectorized hybrids. Hence, there are numerous ways to make hybrids.

This area of research presents great interest to the scientific community and is in constant expansion. We have focused only on the most recent advances in the field. It is obvious that interesting results are obtained by the construction of hybrids. In many cases, not only the biological activity is enhanced but also the selectivity is improved and the toxicities diminished. It is also clear that the hybrid themselves, its entire structure, can provide additional biological properties that only the combination of drugs can do. This review shows the feasibility and great potential of the hybrid approach. The final goal is to further improve the design of the hybrid anticancer agents. This goal is in our reach. To conclude, imagination and creativity are key elements to construct a successful hybrid anticancer agent.

5. Expert opinion

This review presents the latest developments in the design of hybrid and combi-molecule anticancer drugs. The overall objective underlying their development is to build molecules merging two molecular fragments recognized for their individual anticancer activity toward definite targets in the cancer cells to achieve improved activity, selectivity and toxicity of anticancer agents with the aim to reduce the incidence, the mortality and morbidity outcomes of that disease. It is clear that a single agent having the capacity of interacting with several key biological targets in the cell might show significant and even synergistic anticancer properties than targeting single biological target.

The general strategy for the design of such hybrid anticancer drugs is relatively straightforward. First, it involves the structure of known anticancer agent by blending it or simply linking it to a carrier molecule (or another anticancer drug) that target cancer cells more efficiently via a receptor or specific cellular processes leading to improved and even synergized biological properties. There are a number of potential advantages of hybrid anticancer drugs for the patient. First, they have the ability to increase the specificity and strengthen the potency of the anticancer agents. Furthermore, they allow a reduction of the dose and the toxic side effects due to the treatment and offer a synergy between multiple anticancer mechanisms in the cells leading to apoptosis. Additionally, hybrid anticancer drugs allow for a reduction of the induction of chemoresistance mechanisms in tumor and increase the chance of successful treatment.

It should be said that the requirements to design such a hybrid drug are quite evident as not only do they have the potential for high affinity toward the targeted receptor(s) or targeted molecular mechanism(s) but they also have the potential for in vitro and in vivo selectivity on cancer cells. There is also an easiness of synthesis (few and efficient chemical steps are crucial for future commercial development) as well as the potential for large-scale production. It should also be said that there is, as always, the potential for intellectual property protection.

In addition, it must be borne in mind that the future success for the drug targeting approaches will be the use of ‘blended’ or ‘fully integrated’ chemical structures such as those described, for example, by Gleason’s research group [15-17] as well as Jean-Claude’s research group [36,37,39,41,65-68] and many others. The concept of ‘fully integrated’ molecules has great potential because it can be constructed with an appropriate molecular size and physicochemical properties and, thus, it can be more easily accessible and are ‘druggable’ substances.

However, the use of ‘vectorized’ anticancer hybrids shows interesting potential applications. Recent successes were obtained by several research teams. In the future, the best results should arise from compounds that can release the biological active anticancer component at the appropriate location in the tissue and in the cell, as well
as the carrier molecule that can simultaneously act by trig-
gerating either agonistic or antagonistic actions, thereby
enhancing the overall biological effect(s) of the anticancer
component.

So, the future directions for the construct of hybrid anti-
cancer molecules can be divided into two main categories:
‘fully integrated’ and ‘vectorized’ hybrids. The goal of these
hybrid anticancer molecules is to obtain derivatives that will
synergistically act on cancer cells. Clearly, the ‘fully inte-
gerated’ hybrids present great potential as they often lead to
relatively smaller hybrids and thus more drug-like com-

pounds (69). However, the amalgamation of two (or more) dif-
ferent components retaining their respective biological
properties can be challenging. This strategy is at its infancy
and needs to be further investigated. On the other hand,
the synthesis of ‘vectorized’ hybrids is relatively easier. But, yet
again the retention of the properties of the carrier moiety as
well as the anticancer moiety can be difficult. In the future,
we will see refined design where the carrier molecule has
high affinity for its cognate receptor and where the anticancer
moiety possesses higher biological activity than the parent
drug itself. Such combination will lead to new, more selective
and more efficient anticancer therapies devoid of side effects.
Finally, successful development of a hybrid drug will also be
achieved following the requirements of design described
above. Obviously, work is in progress in this field and the
future is bright. Only imagination is the limit to drug develop-
ment.

Declaration of interest

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**Very important review on steroid-based hybrids.**


- **Estradiol–platinum(II) hybrid showing selective in vivo biological activity.**


**A rare example of estradiol–oxaliplatin analogs with good biological activity.**


**Important quaternary ammonium-melphalan conjugate targeting extracellular matrix of cartilage exhibiting good in vitro and in vivo activities.**


**Potent acridine–radionuclide hybrid showing long-lasting effects in the tumor and favorable pharmacokinetic profile.**


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