Recent advancements in Uracil and 5-Fluorouracil hybrids as potential anticancer agents: A review

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ABSTRACT
Cancer is the most dreadful disease and the second main cause of death worldwide. The continuous developments have been going on in order to design potent molecules such that this leading cause of death can be dealt with. In order to decrease the level of toxicity and to improve the selectivity of drugs toward cancer targets, the development of hybrid molecules has become the center of research, and scientists are doing timeless efforts to generate such a hybrid which has got no comparison with the previous developments. The heterocyclic moiety Uracil and many of its derivatives were already exposed as promising anticancer agents. Moreover, coupling of Uracil and 5-Fluorouracil (5-FU) with different pharmacophores has been proven to be an excellent strategy against cancer. Hence, the present review is an effort to collectively represent all the earlier and recent developments of Uracil and 5-FU hybrids reported to have a significant anticancer profile. Expectantly, we can assure that this article can serve as the basis for further developments in Uracil and 5-FU hybrids and will surely motivate the medicinal chemists for producing unique anticancer drug.

INTRODUCTION
Cancer is one of the dreadful, serious, and life-threatening diseases that cause a serious harm to human health. It is the uncontrolled and rapid growth of abnormal cells and the most serious afflictions in the world. Cancer represents one of the leading reasons for death worldwide. According to a survey, one in eight deaths worldwide is occurring due to cancer (Cancer Statistics, 2007). Cancer has become the second most leading cause of death around the world, and approximately 9.6 million deaths have been reported in the year 2018. WHO (2018) evident the cases of liver, stomach, prostate, colorectal, and lung cancers in males; moreover, the cases of thyroid, lung, cervix, colorectal, and breast cancers prevail most commonly in females. Although concerning the treatment of cancer, various discoveries have been made worldwide but a complete cure still proposes a challenge. Evident shows that even after understanding the role of various anticancer agents and the effectiveness of these drugs, there is still a significant research effort that has to be done in the development of such target drug delivery systems and new management therapies for the improvement of both treatment and diagnosis to enhance the safety and efficacy of the therapeutic drugs which makes this a center of research work everywhere (Bae and Park, 2011; Zhu et al., 2013).

Nowadays, a molecular hybrid approach of merging two potential pharmacophores in one molecule has become one of the best effective strategies to beat this deadliest disease. Hence, in the present study, we have discussed all the recently reported hybrids of Uracil or 5-Fluorouracil (5-FU) that exclusively have anticancer properties. This study focuses to assist the medicinal chemists across the world in their molecular designing, who are putting their constant efforts in the research and development of novel hybrid anticancer molecules.

Hybrid molecules
Cancer is a very complex disease and cannot be easily treated with a single drug or with combinations of drugs. Therefore, chemotherapy targets the administration of a high dose of single drug and combination of drugs that led to critical side effects and drug–drug interactions, which has to be minimized. Therefore a technique known as molecular hybridization was discovered that offered a path to overcome these barriers. This technique is based on the inculcation of two or more active compounds into
one molecule without altering their original therapeutic value (Bae and Park, 2011). This technique has been proven productive in the development of various synthetic hybrids that have been found to be more medically effective than their individual components due to their improved affinity and efficacy toward the target sites. Moreover, in this era, molecular hybridization has been proven to be a boon for the designing and development of new and potential antitumor agents (Xu et al., 2019).

Types of hybrid molecules

Molecular hybridization techniques (Fig. 1) can be classified as follows:

**Linking technique**

This technique focuses on linking the two pharmacophores via a flexible linker or spacer. The linkers could be breakable or non-breakable based upon the conditions prevailing at the site of action, that may or may not impart its own therapeutic significance. Cleavable linkage releases the active part of drug at their specific target site whereas non-cleavable linkage retains both pharmacophores until therapeutic action has been achieved.

**Fusing technique**

In this preparation of molecular hybrids is done via covalently linking two bioactive pharmacophores; usually, a condensation reaction between the functional groups of each component is involved in the synthesis of these hybrids.

**Merging technique**

Merge hybrids must have some common parts in their structure. They are small in size as compared to hybrids containing linker and fused hybrid. Usually these hybrids are synthesized by a cyclization reaction between either two acyclic components or between one cyclic and one acyclic component.

All the above-mentioned techniques are being utilized for the synthesis of novel potential hybrids based upon the required pharmacokinetic parameter. Hybrid drug therapy is always found to be better than a single drug therapy because of the advantages (Kucuksayan and Ozben, 2019), which are summarized as follows:

1. The ideal timing window for the hybrid to act upon
2. Enhanced synergistic action of the hybrids in comparison to the concurrent use of separate drugs
3. Attaining limited risk of drug resistance due to its incorporation in hybrid molecule
4. Improved pharmacokinetic features of the hybrids
5. Diminished toxic adverse effects as compared to the administration of multiple agents
6. Improved patient compatibility toward treatment
7. Lowering the cost of treatment

**Designing strategy of hybrid molecules**

For the determination of the safe and effective cure, whole scientific community is putting their constant efforts for the development of potential hybrid molecules that possess unique anticancer properties. The reported studies evident the continuous ongoing research in design and development of potent anticancer drugs via novel chemical and biochemical strategies. The hybrid molecules are basically designed by two major strategies (Fortin and Bérubé, 2013).

**Strategy I (Merging haptorphic moieties of different drugs)**

In this approach, haptorphic moieties of different drugs are merged to obtain new anticancer hybrids. Combination of haptorphic moieties is done in such a way that the molecular structure retains its affinity and potency until it reaches to its biological target.

This approach is further divided into two sub-categories as depicted in Figure 2.

**Blending two drugs having the same target site**

In this approach, haptorphic moieties of different drugs are merged to obtain new anticancer hybrids. Combination of haptorphic moieties is done in such a way that the molecular structure retains its affinity and potency until it reaches to its biological target.

**Indenoisoquinoline-camptothecin hybrids**

These hybrids are obtained by blending two Topoisomerase I inhibitors indenoisoquinoline and camptothecin(1). The hybrids showed good antiproliferative activity in the micro-molar range but they possess lower biological activity than Camptothecin and 5, 11 diketoindenoisoquinoline as parental compounds alone (Fox et al., 2003).

![Figure 1. Different types of molecular hybrids.](image1)

![Figure 2. Hybrid strategy by merging haptorphic moieties of drugs.](image2)
These hybrids are obtained by blending Acridone moiety present in Acronycine and Epoxyfuran moiety present in Psorospermin. This Epoxyfuroacridone (2) exhibits antiproliferative activity in the nanomolar range (Nguyen et al., 2009).

These hybrids are obtained by fusing those molecules which act through different targets or through a different mechanism. These hybrids are blend in such a flexible way that molecule can access easily to each target and counter attack over target achieved.

These hybrids are formed by a combination of phenylethenyl moiety of resveratrol with the coumarin ring system (3); both are reported to have anticancer properties. Moreover, both the moieties act on the same target but via different sites. Coumarin ring acts by different mechanisms on the cancer cells and is also known for induction of apoptosis. These hybrid compounds showed a good anticancer profile with lower IC_{50} values on cell lines used to study. In cell cycle analysis, hybrids reportedly arrest the G2-M-phase and were found to induce the apoptosis too (Belluti et al., 2010).

In these hybrids, two potent anticancer molecular entities that is retinoid moiety of bexarotene and chalcone moiety (4) are fused together. The hybrids show anticancer effect in low micromolar range against colon adenocarcinoma HT-29 cell line (Mizuno et al., 2010).

The second approach deals with a combination of two or more drugs with the help of linker or spacers. The compounds of this category are also recognized as combi-molecules and the connection can be done via a cleavable or non-cleavable linkage. The perspective of non-cleavable linkage is based on the ability of the different molecules to retain their biological properties and efficacy up to they reach to their biological targets. On the other side, the approach of cleavable bond is based on the release of either two active molecules or one active molecule under physiological conditions that prevail at the site of action. To improve poor pharmacokinetic properties of the anticancer drugs or for the slowly deliver of therapeutic entities generally ester, amide or carbamate linkages are incorporated among the molecules. Moreover, to improve the selectivity and specificity toward cancer cells, produg approach is also in a fashion that releases two active drugs directly at the targeted sites (e.g., phosphorylated diethylstilbestrol (DES) prodrugs for prostate cancer) (Fortin and Bérubé, 2013).

This combination strategy further classified into three sub-strategies, which are as follows:

**Combining the two drugs with the same mechanism of action**

In this, moieties having the same mechanism of action are fused together to make combi-molecules so that efficacy and affinity toward the common target are increased. The molecules are fused in such a way that the site of action of the drug is not affected but at last, the hybrid obtained is versatile. Examples are:

**Pyrazoline-coumarin hybrids**

These hybrids were prepared by linking the pyrazolin-5-one heterocyclic ring with coumarin moiety using an acetoxy group as joiner (5), with the aim to have geiparvarin (a coumarin derivative) like anticancer activity on various cancer
cell lines. These hybrids were found to show moderate anticancer activity on different cancer cell lines (Ismail et al., 2010).

1H-1,2,3-triazole tethered Isatin hybrids

They were synthesized by combining two Isatin moieties using 1,2,3-triazole linker in-between (6). The most active hybrids depicted their antiproliferative action in the nanomolar range on different cell lines (Singh et al., 2012).

Combining the two drugs with the different mechanisms of action

These combi-molecules are prepared to counteract multi-biological targets. The purpose of this strategy is to obtain a potent, effective, and useful therapeutic hybrid. This is a synergistic approach to tumor cell via different mechanisms. Examples of these hybrids are as follows:

Nitric oxide (NO) releasing chalcone hybrid

Anticancer activity in tumor cell is found to be mediated via NO release and it may prevent metastasis also. In view of this, NO donating–chalcone hybrids (7) were prepared by tethering NO-releasing nitrate ester (ONO₂) over the moiety of chalcone. Results depicted that chalcone hybrids with NO releasing group effectively inhibit the cancer cells proliferation when studied over various cell line panels (Mourad et al., 2012).

Pyrrolobenzodiazepine–acridone hybrid

Acridones have been reported to possess Deoxyribonucleic acid (DNA) intercalation property and show potent anticancer activity. Conjugates of pyrrolobenzodiazepine and acridone (8) exhibit average lethal dose (LC₅₀) in the nanomolar range for different cancer cell lines and also reported to have DNA-binding property too (Kamal et al., 2004).

Combining drugs that target specific biological tissues

This combi-molecular strategy is used to synthesize novel anticancer hybrids of two different drugs that specifically target on affected tissues. Hybrids prepared using this approach are highly specific, efficacious, and less toxic. Examples of these combi-molecules are as follows:

Nitrogen mustard and tyrosine hybrid

To mimic the same action as of estradiol nucleus, combi-molecules of aromatic nitrogen mustards and tyrosine (9) were designed and synthesized. Antiproliferative assay exhibits that hybrids inhibit the multiplication of prostate, breast, ovarian, and uterine cancer cell lines in micromolar range and also more active than chlorambucil drug (Descôteaux et al., 2012).

Nitroxyl-aziridine hybrid

Aziridine is an important scaffold, which is reported to have a good anticancer profile. To further increase the effectiveness, novel hybrid was designed by linking the aziridinyl to nitroxyl moiety (10). The hybrids are reported to possess activity against mice melanotic melanomas (type of skin cancer) (Kumamoto et al., 2010).

All the above-mentioned contents show the developments that are going on and the hybrid molecules are continuously being produced via different strategies to act as potential anticancer agents. Thus, the hybrid approach is now become a fashion to
develop those potent drugs which nobody has ever thought about. It is mainly expected that hopefully in future, hybrid drugs will definitely decrease the mortality and morbidity rate manifolds.

**Uracil and 5-FU**

Uracil (pyrimidine 2,4 dione) is a common nitrogen containing nucleobases present in the nucleic acid of Ribonucleic acid (RNA). During RNA sequencing, Uracil makes two hydrogen bonds with Adenine, whereas in DNA sequencing the thymine replaces Uracil base. In laboratory, Uracil can be easily prepared by the following methods mentioned in Figure 4 and 5. Uracil undergoes tautomeric shifts and gives rise to amide-imidic acid tautomers. These tautomers are maximum formed and stable at pH 7. The common form of Uracil is amide lactum tautomer.

Concerning to drug designing, Uracil has been considered as a versatile moiety that imparts drug like properties to the designed molecules. Since years, to explore chemotherapeutic potential, various Uracil derivatives, hybrids, metal complexes, and prodrugs are continuously being prepared by making substitutions at N1, N3, C5, and C6 positions (Dimitrova et al., 2017; Newkome and Pandler, 1982). As of now several Uracil derivatives or Uracil fused hybrids are well known for their antiviral, antibacterial, and antitumor potential (Palasz and Ciez, 2015). Due to their DNA intercalation properties, Uracil derivatives and 5-FU interfere in various metabolic pathways of cell division and confer the cytotoxic potential. Both 5-FU and 5-chlorouracil (Fig. 6) were the first Uracil derivatives that showed therapeutic potential (Abdel-Mottaleb and Abdel-Mottaleb, 2016). Among them, 5-FU has had clinical success as a single agent and became a useful drug to treat solid tumors like colon, breast, and other cancers. But 5-FU has not gained much importance due to various limitation associated with it, like poor selectivity, quick drug resistance, undesired side effects, fast catabolism, wide distribution, and short half-life (Fata et al., 1999; Zhang et al., 2008).

So as to reduce the toxicity, side effects, and also to reverse the acquired resistance, several structural modifications have been made by making derivatives, prodrugs, nucleosides, metal complexes, and hybrids of Uracil and 5-FU both. But the present article mainly portrays the earlier and recently reported hybrids of Uracil or 5-FU that have impressive anticancer potential.

**Hybrids of Uracil and 5-FU**

Since from the last two decades, scientists are continuously putting their efforts in making hybrids of Uracil and 5-FU by linking them with other bioactive pharmacophores. Joining of Uracil moiety with other molecule was found to be fruitful especially in the case of anticancer profile. Table 1 contains a list of Uracil/5-FU hybrids synthesized and reported before the year 2014. The table also depicts a short description of anticancer activity of each hybrid.
Table 1. Highlights of earlier reported Uracil/5-FU hybrids with their anti-cancer profile

| Hybrids                       | Structure with anti-cancer profile |
|-------------------------------|-----------------------------------|
| Uracil mustard Distamycin A hybrid (Baraldi et al., 2002) | ![Image of Uracil mustard Distamycin A hybrid](image1) |
| Cancer Cell                  | K562(Human myeloid leukaemia)     |
| IC₅₀ (microMolar)             | 0.07                              |
| 5FU-Diazeneumidolate hybrid (Cai. et al., 2003) | ![Image of 5FU-Diazeneumidolate hybrid](image2) |
| Cancer Cells                 | HeLa(Cervix) DU-145(lung)          |
| ED₅₀ (microMolar)             | 50.0 129.0                        |
| Bis-uracil linker hybrid (Nencka et al., 2006) | ![Image of Bis-uracil linker hybrid](image3) |
| Inhibition against          | Human V79 Expressed cells Human Purified Placenta cells |
| Thymidine Phosphorylases     | IC₅₀ (microMolar) 3.4 2.2          |
| 5FU-Podophyllumotoxin hybrid (Chen et al., 2009) | ![Image of 5FU-Podophyllumotoxin hybrid](image4) |
| Cancer Cell                  | K562(leukaemia) HL60(leukaemia) A-549(lung) |
| IC₅₀ (microMolar)             | 13.2 0.04 <0.01                     |
| 5FU-Camptothecin hybrid (Liu et al., 2011) | ![Image of 5FU-Camptothecin hybrid](image5) |
| Cancer Cell                  | A-549(lung) SGC7901(gastric) HepG2(liver) BGC-823 (gastric) |
| IC₅₀ (microMolar)             | 0.45 2.35 5.28 0.845               |

(Continued)
Recently developed anticancer Uracil/5-FU hybrids

The successful efforts of the scientists in the field of hybrids have kept the interest of many medicinal chemists ongoing. Being impressed by the results of previous researches, in past years, scientists have designed and synthesized some more Uracil/5-FU hybrids and were evaluated for their anticancer profile, which again has shown promising results on different kinds of cancer. Figure 7 displays the novel combinations, which were made after the year 2014 (last five years). Moreover, the detailed description of individual hybrid like their synthetic approach, cancer targets, \( IC_{50} \) values of potent hybrids on panel of cancer cell lines used, and other outcome of the research is mentioned below.

5-Fluorouracil-cholesterol hybrid

Tumor cells engulf more low density lipoprotein (LDL) as compared to normal cells due to over expression of LDL receptors (LDLR) on cancerous cells (Gueddari et al., 1993; Yen et al., 1995). Keeping a view on elevated level of LDLR on cancer cells, Awwad A. Radwan et al. designed and synthesized novel 5-FU-Cholesterol conjugates expecting to be rapidly taken up by LDLR, which subsequently leads to internalization into cancer cells via LDL-receptor-mediated channels. Synthetic approach of desired hybrids (Scheme 1) starts with refluxing cholesterol (12) with dicarboxylic acid anhydride (11) in the presence of pyridine yield the compounds (13-15), which on further agitation with 5-FU in the presence of DCC, 4-dimethylamino-pyridine (DMAP) using dimethyl formamide (DMF), Tetrahydrofuran (THF) (1:1 v/v) solvent at 50°C for 2 days to get the target hybrids (16-18).

Cytotoxic potential of all the hybrids was evaluated against breast cancer cells (MDA-MB-231) and lovo colon cells grown in culture media. Amid all compound 16 (-X-L- = -CH\(_2\)CH\(_2\)-) was found to be the most potent at 100 μM concentration. Moreover, in-vivo anticancer activity was also performed using mice model of Solid Ehrlich Carcinoma (SEC). Results showed that 5FU-cholesterol hybrid 16 produced a significant decrease in tumor volume of SEC on dosing for 3 mg·Kg\(^{-1}\) as compared to the 5-FU (Radwan and Alanazi, 2014). This research represents hybrid 16 could be utilized as a prodrug in future for target delivery of 5-FU via. LDLR mediated pathway into tumor cells.

5-Fluorouracil-colchicine hybrids

Colchicine derivatives have been reported to possess tumor suppression ability and are also regarded as mitotic poisons (Bhattacharyya et al., 2008). Based on some structure-activity relationship (SAR) of colchicine, it was clarified that C-10 analogues of colchicine possess better efficacy and lower toxicity than Colchicine itself (Kozaka et al., 2010). Following this concern, Shen et al. (2015) synthesized a library of novel hybrids having C-10 derivatives of Colchicine with 5-Fluorouracil-1-yl-acetic acid linked through a coupling reaction. Synthetic approach for the most potent hybrid is depicted in Scheme 2. In the first step N\(^{1}\) derivative 20 was easily synthesized by treating

| Hybrids | Structure with anti-cancer profile |
|---------|----------------------------------|
| 5FU-Deoxypodophyllotoxin hybrid (Huang et al., 2012) | ![Structure](image) |
| 5FU-Emodin hybrid (Zhao et al., 2012) | ![Structure](image) |
| Uracil-Istain hybrid (Kumar et al., 2012) | ![Structure](image) |
| Fused Uracil-bischalcone monoadduct hybrid (Solano et al., 2013) | ![Structure](image) |
5-FU (19) with chloroacetic acid in 10% KOH solution at room temperature for 2 hours. Colchicine (21) was initially converted to thiocolchicine (22) in the presence of NaSCH$_3$, and then N-deacetyltiocolchicine compound 23 was obtained by refluxing 22 with 2 mol/L HCl in CH$_2$OH. The target hybrid compound 24 was obtained by acylation of the compound 23 in the presence of 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDCI) and DMAP in dry CH$_2$Cl$_2$ at room temperature.

In-vitro anticancer potential was tested against liver cancer cells (BEL7402), ovarian cancer cells (A2780), lung adenocarcinoma cells (A549), and breast cancer cells (MCF-7) (Shen et al., 2015). The bioassay results depicted that some compounds possess significant activity, but compound 24 was found to be the most effective against all four cell lines with least IC$_{50}$ values (A2780 = 9.5 μM, BEL7402 = 10.2 μM, A549 = 7.8 μM, MCF-7 = 7.5 μM).

### 5-FU-deoxypodophyllotoxin hybrids

Podophyllotoxin (PPT) is a naturally occurring cyclolignan, which have been reported to possess potent cytotoxic effects on different cancer cell lines (Canel et al., 2000). The structural analogue of PPT that is 4-deoxypodophyllotoxin (DPT) is also proved to exhibit antiproliferative and antitumor activity in several cell types (Xiao et al., 2018). Further in in-vivo studies, 4’-demethyl-4-deoxypodophyllotoxin (DDPT) derived from DPT was found to be equipotent to DPT (Huang et al., 2012). Based on the idea of synergistic effect, Guan et al. (2016) prepared compound hybrid series of DDPT and 5-FU using various diamine linkers. Formation of most potent hybrids involves two step syntheses. In step-I, compound 20 was prepared by reacting 5-FU (19) with chloroacetic acid in 10% KOH solution. Then compound 20 was reacted with various N-Boc diamines using 1-[3-(dimethylamino)propyl]-3-ethylcarbodiimide hydrochloride (EDCI), N-hydroxybenzotriazole (HOBt) in DMF to yield compounds 25. Afterwards, compounds of 25 were deprotected using trifluoroacetic acid in dichloromethane to give compounds 26. In step II, DDPT (27) is reacted with succinic anhydride under DMAP and Triethylamine (TEA) in dichloromethane to obtain 28. Eventually, 28 reacted with 26 in the presence of HOBT and EDC to yield desired hybrid 29.

All the synthesized hybrids were evaluated against four different cancer cell lines (liver cancer cells HEPG2, lung cancer cells A549, cervical cancer cells HeLa, and colorectal adenocancer cells HCT-8) and one healthy cell line (human lung fibroblast WI-38), using etoposide, DDPT and 5-FU as standard compounds. Among them hybrid compound 29 (n = 4) is significantly potent against all cell lines with IC$_{50}$ values of 4.03, 0.27, 1.01, and 0.45 μM in HeLa, A549, HCT-8, and HEPG2 cells, respectively. Moreover, compound 29 proved to be less toxic in comparison to 5-FU and etoposide against normal human lung fibroblast cells WI-38. Flow cytometry analysis in A549 cells depicted that compound 29 caused the cell-cycle arrest in the G2/M phase (Guan et al., 2016). Concluding the above study suggests that compound 29 can serve as a novel anticancer drug candidate in future.

Similarly, Xiang et al. (2017) have synthesized numeral hybrid compounds of deoxypodophyllotoxin and 5-FU using various linkers targeting Matrix metalloproteases (MMPs) (Huang et al., 2012). MMPs present in epithelial cells hails from the group of Zinc-dependent proteases that can specifically digest some extracellular matrix components. Some MMPs
specially MMP-2 and MMP-9 reportedly participate in initiating and switching angiogenesis (Stetler-Stevenson, 1999; Van Hinsbergh and Koolwijk, 2008). The β-catenin signaling pathway regulates various processes like cell proliferation, differentiation, apoptosis, and migration (Prakash and Swaminathan, 2015). Any mutation in β-catenin signaling evokes diverse range of cancers (Clevers and Nusse, 2012).

Among all synthesized hybrids, compound 30 was found to possess cytotoxic properties for cancerous cells and least toxic toward non-cancerous cells in comparison to standard Etoposide. In further studies, at a very low concentration (0.1–0.3 μM) compound 30 is found to inhibit proliferation, metastasis, tube formation, and disarray the formed tube-like structures of human umbilical vein endothelial cells. Results also depicted that compound 30 inhibits angiogenesis by decreasing the level of MMP-2 and MMP-9 both (Xiang et al., 2017).

Ferrocenyl containing Uracil hybrids

Uracil-metalloocene hybrids

Metallocene-nucleobase conjugates have become important part of bio-organometallic chemistry. Bi-conjugates of ferrocenyl-nucleobase have already been reported to show good anticancer activity against breast cancer cells MCF-7 and colon cancer cells HT-29 (Kowalski et al., 2015). With the aim to increase anticancer potential by increasing Ferrocenyl nuclear systems, Skiba et al. (2015) synthesized novel metallic mono-, di-, and tri-nuclear Ferrocenyl-Uracil derivatives. All conjugates are having a linker (-CH₂CH₂CH₂-) bridge between Ferrocenyl and Uracil end-groups.

Anticancer screening depicts that di-nuclear hybrid 38 was found to be potent against HT-29 colon carcinoma cells with less IC₅₀ value 4.3 ± 0.7 μM compared to standard Cisplatin (IC₅₀ = 7.5 ± 0.4 μM). Moreover, hybrid 38 (IC₅₀ = 2.4 ± 0.2) produced similar action as standard Cisplatin (IC₅₀ = 2.9 ± 1.0μM) against non-tumor mouse L929 fibroblast cells. Research also showed that incorporation of heavy and lipophilic Fe-CH₂-Fc-group enhanced the cytotoxic effects and also the presence of a single metallocenyl moiety led to inactive conjugates (Skiba et al., 2015). Hence, the dinuclear systems conjugated with organometallic compounds were found to be beneficial for anticancer agents.

Uracil-ferrocenylchalcone hybrids

Ferrocenyl conjugates with other moieties have been proved to be potent anticancer agents (Tan et al., 2012). 5-FU, an antimetabolite drug commonly used for the treatment of cancers like colorectal, stomach, and breast cancer. However, therapeutic importance of 5-FU is decreased due to its poor selectivity, Central Nervous System toxicity and other associated side effects (Pan et al., 2011). Chalcones too possess the cytotoxic potential as they exhibit the same mode of action as Combretastatins (Pettit et al., 2005). This collective information prompted Singh et al. (2018) to synthesize a series of 1,2,3 triazole tethered hybrids of Uracil and Ferrocenylchalcone via. azide alkyne cycloaddition reaction. Synthetic route of the most potent hybrids is shown in Scheme 5.
Synthetic methodology involves the hydride promoted alkylation of 5-substituted Uracils (39) using dibromoalkanes to yield derivatives 40. Then N-alkylazido-5-substituted Uracil derivatives (41) were prepared by reacting 40 with sodium azide (NaN₃) in DMF. Finally, 1H-1,2,3-triazole tethered uracil–ferrocenyl chalcone hybrids 43a-g were prepared using Cu-catalyzed azide-alkyne cycloaddition reaction between N-alkyl azido-uracils (41) and O-propargylated ferrocenyl-chalcone (42). Prepared hybrids were further evaluated for their cytotoxic profile on human leukemia cell lines (CCRF-CEM) and human breast adenocarcinoma cell lines (MDA-MB-468) using Doxorubicin as standard drug. The results depicted that several hybrid compounds 43a-g which are having longer chain spacer (n = 5,6,8) were found to inhibit the cell proliferation up to 70% after 72 hours of 50 μM dosing. Potential compounds with longer chain spacer were also evaluated for their cytotoxic profile against human leukemia cell lines (CCRF-CEM) and human breast adenocarcinoma cell lines (MDA-MB-468) using Doxorubicin as standard drug. The results depicted that several hybrid compounds 43a-g which are having longer chain spacer (n = 5,6,8) were found to inhibit the cell proliferation up to 70% after 72 hours of 50 μM dosing. Potential compounds with longer chain spacer were also evaluated for the cytotoxic profile against normal kidney cell lines (LLC-PK1 ATCC CL-101) and all were found to be non-toxic toward healthy cells, even after 72 hours (Singh et al., 2018).

Uracil N₁ monosubstituted and N₁, N₃ bisubstituted 1,2,3 triazole hybrids

Gregorić et al. (2017) synthesized two novel series of hybrid compounds of pyrimidine 2, 4 dione (Uracil). First series was of 1,4-disubstituted 1,2,3-triazole tethered pyrimidine-2,4-dione hybrids (47a-c) and second was 6-alkylethynylfuro[2,3-d] pyrimidine-2-one–1,2,3-triazole hybrids (48).

The synthetic routes of both the series are mentioned in Scheme 6, reaction initiated with propargylation of 5-bromo uracil (44) that yields N₁-monosubstituted (45) and N₁,N₃-bisubstituted (46) prop-2-ynyl derivatives. First series of compounds that is N₁,N₃-bisubstituted 1,2,3-triazole hybrids of 5-bromouracil (47a-c) was prepared by copper supported azide-alkyne cyclization of 46 by sodium azide (NaN₃) in the presence of sodium ascorbate using solvent DMF. Second line of compounds was prepared by coupling 1,2,3-triazole–5-bromo uracil hybrids (48) with terminal alkynes including cyclopropylethyne, 5-chloropent-1-yne, 1-ethynyl-4-pentylbenzene, and oct-1-yne and the presence of palladium catalyst Tetra-kis (triphenylphosphine) palladium(0) [Pd(PPh₃)₄], N,N-diisopropylethylamine (N,N-DIPEA) and Cu(I) iodide to get the target hybrids 49.

Both the synthesized library of hybrids were further evaluated for their antiproliferative potential on five different cancerous cell lines that are lung cancer cell lines (A549), liver cancer cell lines (HEPG2), ductal pancreatic cancer cell lines (CFPAC-1), cervical carcinoma cell lines (HeLa), and metastatic colorectal cancer cell lines (SW620). Among the first series N,N-1,3-bis-(1,2,3-triazole)-5-bromouracil hybrids 47a-c were found to show the best inhibition toward all cell lines with least IC₅₀ value (Figure 8).

In the second series, 5,6-disubstituted fluoro [2,3-d] pyrimidine-2-one–1,2,3-triazole hybrid 49a exhibits the most potent cytostatic effect especially against HEPG2 and HeLa cell lines as compared to the standard 5-FU (Gregorić et al., 2017).
Uracil-ubenimex hybrid

CD-13 is a multifunctional protein that is abundantly expressed on various cell surfaces. CD-13 is reported to play an important role in cancer invasion (Saiki et al., 1993), migration, angiogenesis, and resistance to apoptosis. Ubenimex is the solely marketed CD-13 inhibitor and immunomodulator in the treatment of leukemia (Ota et al., 1986). Moreover, it is used complimentary with other potential agents in the treatment of cancer (Ota and Uzuka, 1992). Combination therapy of cytotoxic agent 5-FU with other moieties is already proved to reduce the tumor volume incredibly as compared to a single drug (Li et al., 2015). All reported facts stimulated Yuqi Jiang and team to synthesize a novel hybrid prodrug 57, which was supposed to release 5-FU and Ubenimex in-vivo. In hybrid molecule 57, both the potential candidates 5-FU and Ubenimex are connected via –O—CH₂— linker. The synthetic reaction initiated with the formation of 50 from 19 (5-FU) in the presence of 37% oxymethylene. The reaction of 50 with (S)-2-((tert-butoxycarbonyl)-amino)-4-methylpentanoic acid (51) in the presence of 1, 3-dicyclohexyl-carbodiimide (DCC) and DMAP yields acid amide 52. Then deprotection of 52 gives the product 53. On the other side, compound (3S, 4R)-4-amino-3-hydroxy-2-oxo-5-phenylpentanoic acid (54, AHPA) was protected by Boc (ditert-butyl dicarbonate) group to produce 55. Then intermediate 56 was produced by reacting 55 with 53 in the presence of EDCI and 1- HOBt. Then on the treatment of 56 with hydrogen chloride (HCl) in acetidin yields the target hybrid 57.

In-vivo and in-vitro evaluation study depicted that hybrid 57 moderately inhibits CD-13 and found to produce better antiproliferative, antitemtasis, and antiangiogenesis effects than standard 5-FU and Ubenimex. Hybrid 57 shows the best results against A-549 lung cancer cell lines with IC₅₀ value 5.68 μM in comparison to standard 5-FU with IC₅₀ = 16.96 μM and Ubenimex with IC₅₀ = 16.29 μM. Even in 5-FU resistant mice model, hybrid 57 proved more efficient as compared to 5-FU or 5-FU plus Ubenimex (Jiang et al., 2016).

Continuing the same research, Jiang et al. further prepared a novel series of derivatives of hybrid 57 using various linkers to prepare a stable conjugate of 5-FU-ubenimex. Compound 60a-e were prepared from 5-FU (19) by using various Boc protected amino acids and followed by their deprotection as mentioned in Scheme 7. On the other hand, compound 54 was condensed with L-leucine benzyl ester toluene-4-sulfonate and simultaneously Boc protected to form 61, which was further protected by 2,3 dihydropryan and followed by deprotection to give the acid 62. Reaction of 62 with 60-a-e in the presence of EDCI and HOBt gave the intermediates 63a-e. At the end, Boc deprotection of compounds 63a-e with HCl in acetidin yields the desired hybrids 64a-e.

Amidst all compounds hybrid 64a was found to possess the most potent in-vitro antiproliferative action with IC₅₀ = 10–26 μM, pro-apoptosis, antitemtasis, antiangiogenesis, and CD13 inhibition (IC₅₀ = 0.18–5.69 μM) too. Stability and pharmacokinetic study depicted that hybrid 64a released Ubenimex and 5-FU slowly at the desired location. Hence, it was proven to be a good mutual hybrid prodrug of 5-FU and Ubenimex. Also, hybrid 64a also showed superior growth inhibition in 5-FU-resistant mice model with liver cancer (Jiang et al., 2018).

Uracil-camptothecin hybrids

As Camptothecin has been reported as an important class of antitumor agents (Wall et al., 1966), Di-Zao Li et al. synthesized...
series of novel ester linkage conjugates of Uracil & Camptothecin. Uracil C₅-substituted derivatives (65a-e) were derivatized using chloroacetic acid in the presence of KOH in water. Further N₁ substituted derivatives (66a-e) were condensed with 7-ethyl camptothecine (67) in the presence of EDCI, DMAP, and pyridine to yield the target hybrids (68a-e).

All the novel conjugates were tested for antitumor activity against five different cancer cell lines (A549, BEL7402, BGC-823, HCT-8, and A2780). These results depicted that the hybrid 68b (IC₅₀ = 0.007–0.147 μM) & 68c (IC₅₀ = 0.002–0.670 μM) possess the best efficacy against all cancer cell panel in comparison to individual Camptothecin and Topotecan (standard).
Furthermore, in-vivo evaluation of compound 68b & 68c (Fig. 9) for anticancer activity against mice liver carcinoma H$_{22}$ depicted that they have a nearly similar response as of Paclitaxel and Cyclophosphamide.

Similar to Camptothecin, hybrid 68b was also found to inhibit topoisomerase-I more efficiently (Li et al., 2017). Hence, hybrid 68b with high potency and lower toxicity can be developed as a potential drug candidate in future.

Uracil-oleanolic acid hybrid

Oleanolic acid (3β-hydroxyolean-12-en-28-oic acid) belongs to the family of oleanane pentacyclic triterpenes, which is reported to be isolated from more than 1620 different plant species of food and herbs (Pollier and Goossens, 2012). Oleanolic acid analogues have been proved to have different biological activities including antiproliferative activity in solid tumor cells. SAR studies of oleanolic acid showed that structural modification at C-3 and C-28 improves cytotoxic properties against prostate cancer (PC-3), lung cancer (A549), and breast cancer (MCF-7) cell lines (Hao et al., 2013). Being inspired by the evidence, Mo et al. (2016) synthesized the conjugates of Acyl-oleanolic acid and Uracil. Synthetic pathway starts with the treatment of oleanolic acid (69) (1 equiv) with anhydride (1.5 equiv) and DMAP (0.1 equiv) in anhydrous CH$_2$Cl$_2$/pyridine at room temperature to yield 3-O-acyl derivatives (70a-c). These derivatives were then initially treated with oxalyl chloride (18 equiv) to give the corresponding acyl chloride, which was further treated with Uracil (3 equiv) in the presence of Et$_3$N (triethyl amine) to produce final acyl oleanolic acid-uracil hybrids (71a-c).
All synthesized hybrids were evaluated against five cancer cell lines (HEP-G2, A549, BGC-823, MCF-7, and PC-3) for cytotoxic potential taking Oleanolic acid and 5-FU as standard. Almost all the conjugates proved to be cytotoxic with IC<sub>50</sub> value of less than 10 μM. Among them, compound 71c (mentioned below) was found to be the most effective against all cell lines with IC<sub>50</sub> ranging from 0.22 to 6.99 μM. Moreover, unlike other compounds, compound 71c was found to be the least cytotoxic to healthy liver cell line (HL-7702). Further cell cycle analysis depicted that compound 71c could trigger apoptosis by activating caspase-3/9 and arrest the G1 phase of HEP-G2 cells (Mo et al., 2016).

Structure activity relationship (uracil hybrids)

On the thorough study of earlier and recently reported Uracil and 5-FU hybrids, it can be summarized via basic Uracil moiety (Fig. 10) that:

1. N<sub>1</sub> and N<sub>3</sub> are the foremost hybridization sites for the generation of mono and bifunctional hybrids.
2. In order to provide the rigidity, other pharmacophores linked directly to N<sub>1</sub> and N<sub>3</sub> through ester or amide linkage (Uracil-camptothecine hybrid) and flexible hybrids are obtained by linking Uracil with other pharmacophores via a chain linker (Uracil-Ferrocenylchalcone hybrids, 5FU-deoxypodophyllotoxin hybrids, etc.).
3. Oxo groups at second and fourth positions usually participate in h-bond formation with amino acid residues of target protein. Replacement of “=O” (oxo) with “=S” (thio group) produces another class of anticancer agents that is thiouracils (El-Naggar et al., 2017). Sometime
oxo groups are utilized in making fused hybrids also (furan fused triazole linked hybrids, 49a)

4. Use of long-chain linker at N₁, N₃ and alkyl group substitution at C₆ yield hybrid having good cellular penetration power.

5. Halogen substitution at C₅ position increases the cytotoxic potential. Fluorine produces the maximum inhibition and the order is F>Cl>Br>I>H. Inhibitory potential of 5-FU is reported to be increased via hybridization with other pharmacophores (5FU-Cochine hybrids, 5FU-cholesterol hybrids, 5FU-PPT hybrids, etc.).

6. C₄–C₅ double bond is the best site for making adduct via Diels-Alder reaction Or making fused hybrids with other moieties (Uracil-bischalcone hybrids).

Scheme 8. Synthetic approach toward 5-FU-Ubenimex hybrids (using various linkers)

Scheme 9. Synthetic scheme of uracil-camptothecin hybrids
Hence, the present study proves the versatility of Uracil moiety, which encourages the medicinal chemistry for its consideration in drug designing strategies with other pharmacophores to produce multi-targeted hybrids.

CONCLUSION

From several years, continuous efforts are being made for increasing the efficacy and target specificity of 5-FU and other Uracil derivatives by making their prodrugs, hybrids, conjugates, metal-ligand complexes, etc. Among them, in cancer treatment, the hybrid approach remains one of the best strategies to overcome the limitations associated with single drug component and multiple dosing of drugs. This prompted us to collectively depict the anticancer potential of recently developed Uracil and 5-FU hybrids. Based on the outcomes of all the hybrids in concern to their IC\textsubscript{50} values and other pharmacological results, it can be positively concluded that making hybrids of Uracil and 5-FU are found to be beneficial in terms of cancer cell specificity, multiple drug resistance, target drug delivery, drug toxicity, and dose reduction. Thus, this review study suggests that there is still a significant scope in developing novel anticancer hybrid drugs by placing an active pharmacophore at different positions of Uracil nucleus. Hopefully, the continuous efforts of medicinal chemists of hybridization of Uracil or 5-FU with a diversity of potential molecules will probably discover a magical anticancer hybrid, which will be proven as a boon in future.

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CONFLICT OF INTEREST

The author declared that there is no conflict of interest.

ABBREVIATIONS

| Abbreviation | Full Form |
|--------------|-----------|
| AHPA         | (3S,4R)-4-amino-3-hydroxy-2-oxo-5-phenylpentanoic acid |
| DCC          | N,N'-Dicyclohexylcarbodiimide |
| DCM          | Dichloromethane |

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