

Antibody drug conjugates for tumor targeting – novel conjugation chemistries and the promise of non-IgG binding proteins

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Abstract

Antibody-drug conjugates (ADCs) have emerged as a promising class of anti-cancer agents, combining the specificity of antibodies for tumor targeting and the destructive potential of highly potent drugs as payload. An essential component of these immunoconjugates is a bifunctional linker capable of reacting with the antibody and the payload to assemble a functional entity. Linker design is fundamental, as it must provide high stability in the circulation to prevent premature drug release, but be capable of releasing the active drug inside the target cell upon receptor-mediated endocytosis. Although ADCs have demonstrated an increased therapeutic window, compared to conventional chemotherapy in recent clinical trials, therapeutic success rates are still far from optimal. To explore other regimes of half-life variation and drug conjugation stoichiometries, it is necessary to investigate additional binding proteins which offer access to a wide range of formats, all with molecularly defined drug conjugation. Here, we delineate recent progress with site-specific and biorthogonal conjugation chemistries, and discuss alternative, biophysically more stable protein scaffolds like Designed Ankyrin Repeat Proteins (DARPs), which may provide such additional engineering opportunities for drug conjugates with improved pharmacological performance.

1. Introduction

The fundamental problem of all chemotherapeutic agents is their small therapeutic window. While most compounds in use today preferentially attack proliferating cells, classical chemotherapy causes side effects which limit the tolerated doses below the clinically effective ones. To increase the therapeutic window, dose-limiting toxicity must be reduced while at the same time effectiveness must be maintained. Antibody-drug conjugates (ADCs) combine the unique specificity of antibodies for tumor-associated antigens to discriminate between normal and malignant cells, and the cytotoxic effect of a small molecule drug as payload ¹⁻³.

Nonetheless, far from being a magic bullet, ADCs normally will have several liabilities as well: on-target, by the target antigen being expressed in healthy tissues, and off-target, on the one hand by an unspecific uptake of the whole conjugate by healthy cells, and on the other, by the drug coming off the antibody. Additionally, the high specificity offers an escape mechanism to the tumor cells by down-regulating the relevant surface antigen ⁴. These general considerations emphasize the importance of a judicious choice of the target antigen for minimizing on-target toxicity, while molecular engineering optimizing half-lives and general molecular properties is needed for minimizing off-target toxicity of the conjugate. Finally, linker chemistries must be considered to optimize toxin release after cellular uptake, but not prematurely.

The first cytotoxic agents used for antibody payloading were vinblastine, doxorubicin, methotrexate, and melphalan. In the most promising of these first-generation ADCs, doxorubicin was attached to the anti-Lewis Y antibody BR96, using an acid-labile hydrazone bond. Despite impressive effects in tumor xenograft models ⁵, BR96-doxorubicin, however, demonstrated very low antitumor activity and tolerability in patients ^{6, 7}. Binding of the antibody to normal epithelial tissues, low drug potency, and insufficient stability of the conjugate were made responsible for the clinical failure of this first-generation ADC. In the meantime, the spectrum of tumor-selective antigens has increased and more potent anti-cancer agents with cellular IC₅₀ values in the pM range have become available for antibody payloading ².

Another important element in ADC design is the choice of the linker which connects the chemically different targeting molecules to a functional chemical entity and maintains the distinct biological functions of the components. To provide high potency and tolerability, the linker must be stable to prevent premature drug release in the circulation but capable of releasing it inside the cell upon receptor-mediated endocytosis, such that the (usually)

hydrophobic drug can cross the endo-lysosomal membrane into the cytosol. Currently, two categories of linkers, cleavable and non-cleavable, are used, which address these requirements by different mechanisms². The next crucial step is then to attach the linker-drug constructs to specific reactive sites in the antibody.

With common antibodies, conjugation is possible at lysines, cysteines or N-glycans. The conjugation at lysines, considering the large number in an IgG, will be stochastic and result in heterogeneous synthetic products characterized by variable drug-antibody ratios (DARs), at least over a certain range. The conjugation at cysteines can either be to disulfides (typically at the hinge), which need to be reduced first, or to genetically introduced cysteines⁸. While reaction conditions have been optimized to obtain desired DARs, pharmacological performance may well depend not only on the DAR, but also on the precise location of the drug on the binding protein⁹.

Recent biotechnological advances have provided a multitude of protein modification strategies to better fix the number and location of payload attachment in ADCs^{8, 10}. Also, a number of enzymatic conjugation strategies have been reported that allow the attachment of the drug to a tag introduced to the antibody¹¹. In addition, alternative non-IgG formats have become available, which can be engineered to a variety of half-lives, expressed at very high yields and better tolerate the engineering procedures required for well-defined DARs and optimal efficacy^{12, 13}. Here, we delineate recent progress in ADC design and the perspectives for engineering novel tailor-made drug-conjugated binding protein formats with desired pharmacological properties.

2. Clinical benefit for tumor-targeting ADCs

Owing to a better understanding of the pharmacological determinants of tumor targeting and recent progress in protein engineering, bioconjugation chemistries and the generation of highly potent payloads, the ADC pipeline is rapidly growing with currently more than 100 entities in clinical trials. For oncology indications, however, clinical results are still far from exciting and many challenges remain to help this technology establish its place in cancer therapy (www.clinicaltrials.gov).

ADCs approved by the US Food and Drug Administration (FDA) or currently in advanced clinical trials are shown in Table 1. So far, only three ADCs were approved by the FDA. They employ either the tubulin polymerization inhibitors monomethyl auristatin E and F (MMAE, MMAF), derivatives of maytansine or the DNA-strand breaking calicheamicin

(Table 1). These payloads outperform the potency of classical chemotherapeutic drugs by a factor of 1000². As the first, gemtuzumab ozogamicin (Mylotarg[®]), which consists of an anti-CD33 antibody linked to calicheamicin, was granted accelerated approval in 2000 for the treatment of relapsed acute myeloid leukemia (AML)¹⁴. It was withdrawn from the market 10 years later, due to excessive toxicity and lack of anti-tumor activity in a post-approval clinical trial with newly diagnosed AML¹⁵. Since then, several randomized studies have been completed which nevertheless demonstrate efficacy of this ADC for the same indication using a modified dosing regimen¹⁶. It may well be that gemtuzumab ozogamicin will soon find reapproval for this disease. However, this history impressively shows how narrow the therapeutic window in ADCs really can be, and that clinical reality can be very different from seemingly straightforward concepts.

The next approved candidate was brentuximab vedotin (Adcetris[®]), an anti-CD30-MMAE immunoconjugate, which obtained accelerated FDA approval for the treatment of Hodgkin's lymphoma and anaplastic large cell lymphoma in 2011¹⁷. In 2013 finally, ado-trastuzumab emtansine (T-DM1/Kadcyla[®]), an ADC combining an anti-HER2-antibody with the maytansinoid DM1, obtained market approval for the treatment of HER2-positive metastatic breast cancer (Table 1)¹⁸. However, the recently reported failure of Kadcyla[®] to meet the primary endpoint of a phase III study in breast cancer patients (NCT01120184; BO22589) denotes an unpleasant setback in the field. A deeper understanding of the intrinsic properties of the distinct functional components is key to more successful ADC design in the future and to improve the perspectives of the whole ADC concept for cancer therapy.

3. Linker chemistries

One critical component of the ADC entity is the linker tethering the cytotoxin to the antibody. To achieve a maximal therapeutic window, it must be stable in the circulation, yet allow efficient drug release inside the cell upon receptor-mediated endocytosis. Therefore, it must exploit the differences between the extra- and intracellular environment, respect the properties of the target antigen for internalization and must be compatible with the chemistry of the payload. Linker design, hence, does not follow predefined guidelines and needs to be determined empirically for each ADC^{2,3}.

Currently used linkers in ADCs are either cleavable or non-cleavable¹. Payloads not tolerating substitutions without loss of activity require cleavable linkage which depends on intracellular processing such as acidic hydrolysis or enzymatic cleavage in the endo/lysosome,

leading to release and thus activation of the drug. This allows bystander killing of non-targeted tumor cells when hydrophobic drugs are used, which is particularly advantageous if antigens are heterogeneously expressed in tumors ¹⁹. Acid-labile hydrazone linkers were among the first cleavable linkers used in ADCs. Upon internalization, the acidic pH in endosomes (pH 5.0-6.5) and lysosomes (pH 4.5-5.0) leads to hydrolysis of the hydrazone and subsequent release of the drug ^{2, 20}. The serum stability of hydrazone linkers, however, is poor ^{21, 22}. The low clinical efficacy and the safety concerns of gemtuzumab ozogamicin were mainly attributed to this linker instability and premature drug release in the circulation ^{5, 16, 23}. Cleavable disulfide linkers, in turn, exploit the high concentration of thiols, such as glutathione, in the cytoplasm, which reduce a disulfide bond in the linker to liberate the payload ^{1, 24}. To decrease reduction by reactive thiols in the serum, the stability of disulfides can be increased by introducing methyl groups flanking the disulfide bond to generate a sterically protected disulfide linker ²⁵. Although several disulfide-linked ADCs are currently under clinical investigation (Table 1), more stable cleavable linkers are engineered in the form of lysosomal protease substrates, e.g. containing a valine-citrulline dipeptide bond, which is specifically cleaved by cathepsin B ²⁶⁻²⁸.

Non-cleavable linkers, on the other hand, avoid premature drug release in the circulation by design ¹. Instead, the ADC must be proteolytically degraded in lysosomes and the payload is released as an active metabolite along with the amino acid it was conjugated to, i.e., usually a cysteine or lysine ^{19, 29}. Although the charge of a lysine-*N*^E-coupled drug metabolite may hamper endo-lysosomal escape, it prevents externalization and bystander killing ^{29, 30}. This will, on the one hand, lead to enhanced specificity, but on the other hand, limit the action of the drug to the very cell that has taken up the ADC.

Furthermore, as the linker forms part of the active drug, it can be designed to add additional valuable functional properties to the drug, like prevention of MDR1 efflux and thus drug resistance, by making it more hydrophilic, e.g., in the form of a PEG₄Mal linker ³¹.

4. Payloads

Natural products and synthetic chemistry provide a plethora of cytotoxins of which only few have been found suitable for use in ADCs ^{32, 33}. First, the drug's target must be crucial for cell viability to achieve highest cytotoxicity even at the low concentrations which can be realistically achieved upon internalization. Ideally, the number of drug molecules required to kill a cell are well below the number which is delivered by ADCs, that depends on

the DAR and the number of ADCs taken up by a cell in a clinical setting. Data using radiolabeled humanized antibodies suggests that localization in tumors does not exceed 0.05% of the injected dose per gram tissue^{2, 34}. This, in turn, leads to the unavoidable conclusion that the vast majority of the ADC does not end up in tumor cells.

Drug activation depends on the linker chemistry and occurs after cleavage or by lysosomal degradation¹. To show selectivity upon antigen-specific uptake, the payloads' target must be located inside the tumor cell. Many highly potent natural toxins act on the surface of cells by blocking ion channels, disturbing blood clotting etc. and are thus unsuitable, as cell specificity would not be achievable by a conjugated antibody. On top of that, the payload's molecular properties are important, too. It must be small in size to reduce immunogenicity, soluble under aqueous conjugation conditions to prevent aggregation, and compatible with the linker chemistry³⁵.

Consequently, as mentioned above, all ADCs approved or under late clinical investigation are payloaded with new generation drugs dominated by the DNA-strand breaking calicheamicins^{25, 36, 37}, duocarmycins³⁸, the tubulin-targeting maytansines^{39, 40} and auristatins^{17, 41}. The mechanisms of action and the chemistry of the coupling and release reactions of these warheads have been described in detail elsewhere^{1, 42, 43}. Table 1 summarizes representative examples of clinically advanced ADCs using these highly potent drugs as payloads.

5. Conjugation chemistries

5.1. Site-selective conjugation and the drug to antibody ratio

Conjugation site-selectivity and stoichiometrically controlled conjugation of cytotoxic payloads to antibodies and other non-IgG binding proteins is crucial for tumor targeting. So far, all chemistries used for linker-drug conjugation to antibodies in late clinical trials have been based on solvent accessible cysteine and lysine residues through either thiol-maleimide coupling (e.g. brentuximab vedotin)¹⁷ or amine NHS-ester coupling (e.g. ado-trastuzumab emtansine)⁴⁴, respectively (Table 1 and Table 2). As IgGs carry a variable number of lysine side-chains, this yields heterogeneous products with variable DARs and inter-batch variations. For instance, a typical modification of an IgG with an NHS-ester yields an average DAR of 0-8. Thus, the 40-86 lysine residues on the antibody surface are modified to a variable degree, resulting in a sample with potentially 4.5 million different molecules in terms of regioisomerism and drug load^{45, 46}. If thiol-maleimide coupling is used instead, cysteine

conjugation occurs after mild reduction of the four inter-chain disulfide bonds in the hinge region of an IgG₁. Although conjugation is limited to these eight exposed sulfhydryl groups, as clinically used IgG₁ typically do not have Cys residues in the CDRs, and thus a higher coupling specificity compared to lysines can be achieved, it can still yield more than hundred different ADC species^{46, 47}, depending on the degree of loading and considering regioisomers. It must be noted that both DAR and conjugation sites are important for ADC function, as they influence the molecular properties through the exposed drug moiety. Whereas a drug load of 2 seems to provide the best pharmacological performance⁴⁷, the site of drug conjugation determines linkage stability and thus the ADC's tolerability and efficacy⁹.

As a consequence of the limited site-selectivity of drug conjugation with conventional linkage strategies, even the clinically approved ADCs represent mixtures of regioisomers with different DARs, each of the molecular species showing a different cytotoxicity and safety profile^{47, 48}. Unconjugated antibodies, which can be hardly separated from the preparations, block potential binding sites on the tumor surface and thus lower ADC efficacy, whereas drug conjugates with high DAR show increased off-target toxicity and are prone to aggregation, which narrows the therapeutic window⁴⁹. This delineates that current ADC design is still far from optimal. To engineer ADCs for higher efficacy and tolerability, site-selective conjugation is mandatory to better control the number and attachment site of payloads.

Recently, Pillow et al.⁴⁸ reported a markedly improved homogeneity of trastuzumab-DM1 generated by engineering cysteine residues at defined sites in the antibody. Since the exposed cysteines are derivatized with cysteine or glutathione in the secretory pathway of the host cell, a reduction/oxidation process is required (THIOMAB technology), which reforms the hinge and C_L-C_H disulfides⁵⁰. The better defined DAR of 2 to 4 and a novel linker technique for DM1 increased the efficacy and safety of the resulting ADC⁴⁸. This must be seen in the context of recent findings that in terms of efficacy, less payload is more⁴⁷.

Another technique to site-specifically conjugate payloads to antibodies is the use of N-glycans for attachment. Major limitations of this technique, however, are the difficulty to obtain homogeneous glycan structures and to avoid unwanted oxidations of the proteins resulting from chemical modifications. Furthermore, the glycan structure is important for desired antibody functions like ADCC and, when modified, can generate new highly immunogenic epitopes⁸.

5.2 Bioorthogonal conjugation

In view of the many downsides associated with uncontrolled payloading, engineering a unique, orthogonal functional group into proteins, which then can be coupled to a specific reaction partner in a bioorthogonal manner, is appealing also for antibody drug conjugation. In this constellation, two components, which are fully complementary and, additionally, orthogonal to nature's functional groups on protein (thiols, alcohols or amines), react to form a chemical bond. These components must be stable and small, whereas the reaction must be fast, and yet conditions must be so mild that the reaction can be conducted with proteins⁵¹. The concept of orthogonal chemistry aims to avoid unspecific side-reactions and allows stoichiometrically defined modifications. Here, we briefly discuss the various biorthogonal conjugation chemistries with potential for ADC generation. The use of enzymes, either for the conjugation reaction itself or the incorporation of unique functional groups into proteins, also represents a valid concept for drug conjugation, the benefits and drawbacks of which are described elsewhere^{8, 11, 51}.

The first truly bioorthogonal reaction for protein modification was reported in 2000 using the Staudinger ligation. Derived from the original Staudinger reaction, a reaction between a phosphine and an azide leading to an amine by subsequent hydrolysis, was modified to form a stable amide bond linkage⁵², by installing an electrophilic trap at the phosphine component. A significant drawback of this ligation reaction is the oxygen sensitivity of the phosphine reagents and the slow reaction rate constant, and thus it is not well suited for conjugation of drugs to protein and not used nowadays.

5.3 Click chemistries for bioconjugation

Another approach to biorthogonal protein modification exploits the 1, 3-dipolar cycloaddition for linking biological components. In this Cu(I)-catalyzed azide-alkyne cycloaddition (CuAAC) an azide reacts with a terminal alkyne to form a stable triazole (Table 2)^{53, 54}. The higher reaction rate and the stability of the reactants has made this reaction appealing and widely used for bioconjugation⁵⁵. Its dependence on cytotoxic copper, however, limits the use of such products in biological systems. A copper-free alternative is the strain-promoted azide-alkyne cycloaddition (SPAAC), also denoted click chemistry, which uses ring-strained cyclooctynes instead of terminal alkynes (Table 2)⁵⁶. To improve the moderate reaction rates, various derivatives such as fluorinated⁵⁷, benzoannulated^{58, 59} and cyclopropanated⁶⁰ cyclooctynes, have been synthesized. Noteworthy are the cyclopropanated variant bicyclo[6.1.0]nonyne (BCN) and the benzoannulated derivative dibenzocyclooctyne

(DBCO), also denoted as aza-dibenzocyclooctyne (DIBAC). Both reactants improve reaction rates 100-fold over cyclooctyne. Altogether, DBCO was found to best combine high stability and efficiency with high hydrophilicity and fast reaction kinetics for the classical SPAAC reaction.

For protein-drug conjugation, it would be most appealing if the site of drug conjugation in the protein can be freely chosen. This is the case with non-natural amino acids containing azides as they can replace methionines. The aminoacyl tRNA synthase for methionine in *E. coli* accepts the methionine-surrogate azidohomoalanine (Aha), and thus in methionine-auxotrophic *E. coli* strains, after simple Met depletion of the culture, Aha can be introduced without any other changes in the *E. coli* strain⁶¹. However, this requires that the protein can be produced in *E. coli* and thus this strategy favors alternative non-IgG scaffolds.

Nevertheless, despite the use of rate-optimized cyclooctynes like DBCO and BCN, the described reactions are comparably slow (0.1 - 0.3 M⁻¹s⁻¹), and unspecific coupling to irrelevant reaction partners present on cell surfaces cannot be excluded and limit the orthogonality of the reaction^{59, 60, 62}. On the other hand, as bioconjugation partners of ADCs are usually very pure, such side reactions are unlikely to occur and the stability of the components used for cycloaddition remains as an advantage.

The rate constant of SPAAC with BCN can be highly accelerated using electron-poor, aromatic azide components instead of Aha⁶³. In another study, Borrmann et al.⁶⁴ reported even more improved rates of cycloaddition by several orders of magnitude using quinones instead of azides as reaction partner for BCN. Moreover, this reaction can be temporally controlled by oxidation of inert catechols to the reactive quinone. To make these reactions applicable to proteins, they must first be charged with aromatic azides, BCN or quinones in a stoichiometrically defined, site-specific manner. This is no longer possible with a simple *met* strain of *E. coli*, but requires amber-suppression technology for site-specific incorporation of BCN-lysine or other non-natural amino acids carrying functional groups like quinones or norbornenes⁶⁵⁻⁷². So far, this technology was only used for imaging agents, as it shows unfavorably low expression yields⁶⁶.

Also in our hands, amber suppression protein variants showed comparatively low expression and also inhomogeneity, since the efficiency of suppression varies with the amber site. This requires engineering for purification and thus limits the freedom of molecular design (unpublished data). Although this may in principle be overcome using sequence optimization⁷³ and adapted *E. coli* strains⁷⁴, the problem remains that, compared to azide-

containing non-natural amino acids like Aha, non-natural amino acids like BCN-lysine are rather expensive, and, to our knowledge, bacterial strains and vectors carrying tRNA/RS pairs for the incorporation of specific non-natural amino acids have not been made commercially available.

Using the amber suppression technology to site specifically incorporate *para*-acetylphenylalanine (*pAF*) in antibodies and to conjugate the drug payload via oxime ligation (Table 2) ^{10, 75, 76}, new biologicals could be generated. This technology, when applied to trastuzumab emtansine, yields a defined DAR of 2, and the authors believe that the antitumor activity and stability is increased compared to drug conjugates produced with the THIOMAB method. A possible explanation might be that a retro-Michael addition, leading to the transfer of drugs conjugated to cysteines to free thiols in blood serum components, may have partially inactivated the ADC ⁷⁶⁻⁷⁸. However, the authors do not provide convincing data showing that their own preparation of the THIOMAB antibody had a DAR of 2, as it was published by Junutula *et al.* ⁵⁰. Furthermore the *pAF* incorporation still suffers from low expression yields, which can only be overcome by extensive cell line engineering, and the oxime ligation exhibits low reaction rates, leading to reaction times up to 48 h and is performed at pH 4-4.5, which is not tolerated by all proteins.

5.4 The inverse-electron-demand Diels-Alder reaction for bioconjugation

The highest rate constants of bioconjugation can be achieved by using the inverse-electron-demand Diels-Alder reaction of tetrazines and strained alkenes for bioconjugation ⁷⁹. As it has been reported only recently, this results from a decreased closed-shell electron-electron repulsion between the reaction partners ⁸⁰. Nothing beats rate constants of up to $10^6 \text{ M}^{-1}\text{s}^{-1}$ of *s*-tetrazines with *trans*-cyclooctene (TCO)-derivatives (Table 2). Since TCO and tetrazines can be incorporated in proteins using amber-suppression, numerous applications for imaging purposes were reported ^{72, 81, 82}. A downside lies in the diminished stability of the most reactive tetrazines in physiological buffers, and, as mentioned above, broad use of the amber-suppression-technique is still limited by the high costs of the reagents, low expression yields and restrictions in where the modification site can be introduced. Nonetheless, if these obstacles can be overcome, the value of this protein payloading technique for ADC generation would be immense.

6. Binding proteins – antibodies and alternative non-IgG formats

The key function of the antibody in ADCs is binding to its target antigen, which is ideally expressed on the surface of tumor cells in high copy numbers and absent or at least low in normal vital tissues. Upon binding, the attached payload is delivered into the cell by receptor-mediated endocytosis, detached from the antibody by a variety of mechanisms, and transferred to the cytosol, where it acts on its target. An intrinsic property of the full-IgG format is its binding to Fc receptors on immune effector cells, which may further boost the ADC's cell killing activity. The clinical benefit of this additional effector function, however, remains to be demonstrated ⁴⁹. In addition, binding to the FcRn receptor increases the circulation half-life and, hence, tumor localization. However, the comparison of a diabody-ADC with an IgG-ADC with similar DARs showed only a 3-fold decreased antitumor activity of the diabody-ADC, despite a 30-times lower level of exposure ⁸³. The improved tumor penetration of smaller conjugates may at least partly compensate the shorter serum half-life and thus help explain this finding ⁴⁹.

From these data it can be concluded that, by engineering half-life, size, avidity or other properties of different binding protein formats over a wide range, which is not possible with classical IgGs, the best combination of high activity in the relevant (tumor) tissue and low off-target toxicity can be found. Another important advantage of smaller protein scaffolds, especially when they can be produced in *E. coli*, lies in the broader options for well-defined drug conjugation, which may be a downside of the classical IgG format.

Fab- and scFv-ADCs can be engineered for drug conjugation, and indeed, with such size-minimized IgG binding proteins, DARs of 1 have been achieved and several IgG-fragments are currently under preclinical evaluation ⁴⁹. Axup *et al.* ⁸⁴ recently generated a highly potent Fab-auristatin using amber suppression for the incorporation of *pAF* and oxime ligation for drug conjugation. Novel bioorthogonal chemistries like click chemistry or the inverse-electron-demand Diels-Alder reaction, however, have not yet been applied to antibody fragments. Hence, non-IgG derived binding proteins allowing the application of new bioorthogonal chemistries for fast and site-specific drug conjugation with high yields and permitting the screening of a wide range of pharmacological and molecular properties, are desired.

As an alternative to antibodies and their fragments, various non-IgG binding proteins with improved biophysical properties have been generated for tumor targeting. Their robust nature allows expression in large quantities, they can be engineered to various formats, from

mono-, bi- to tetravalent, and with a range of half-life extension features, and they can better tolerate the introduction of reactive groups for site-specific and bioorthogonal conjugation^{12, 85}. These properties introduced in the design also make these formats compatible with the novel bioorthogonal conjugation chemistries described above. Despite this advantage for bioconjugate engineering, so far only DARPins have been used for drug conjugation⁸⁶. The potential of bioorthogonally assembled peptide-drug conjugates for tumor targeting is described elsewhere⁸⁷.

DARPins have been introduced recently as a new class of binding proteins which are superior to antibodies for various biomedical applications¹³. Besides showing very high expression yields in *E. coli*, DARPins are much more stable than antibodies and have favorable biophysical properties which increase their freedom of engineering as they e.g. carry no cysteine and no essential methionine⁸⁸. Moreover, DARPins of very high affinity can be readily generated using well-established selection techniques such as ribosome display and phage display as previously demonstrated¹³. We recently described the successful generation and preclinical testing of DARPins selected for high stability and affinity, directed against well-internalizing cell surface antigens on solid tumors, which are available for tailor-made drug conjugation⁸⁹⁻⁹¹.

DARPins provide a valuable platform also for manufacturing bioconjugates with various chemistries. First, the lack of native cysteines enables site-directed introduction of these residues, e.g. at the C-terminus for specific maleimide-based conjugation of effector functions, including the cytotoxic payloads known from classical ADCs (Figure 1). Of particular interest for drug conjugation of DARPins is also the lack of conserved methionines in the protein scaffold. This allows for the facile incorporation of Aha and the expression of azide-DARPins using methionine-depleted bacterial cultures^{61, 85}, which can be done in very high yield and at large scales. The only Met present in the original design, besides the initiator codon, is in the N-capping repeat, which can be exchanged to leucine without affecting the biophysical properties of the protein and is already replaced in some DARPins through the random mutagenesis in ribosome display⁸⁵. Additionally, DARPins are usually expressed with an N-terminal MRGSH₆ tag, from which the methionine is not cleaved⁹², and this is also true when an amino acid analog is introduced⁹³. Conversely, if the second amino acid is small (e.g., Ala, Gly or Ser), the analog will be cleaved off, allowing the introduction of a unique methionine surrogate such as Aha at desired positions elsewhere in the chain (Figure 1)⁸⁵. The possibility to engineer dual functionality (azide and thiol) into DARPins enables the

design of tailor-made drug conjugates with desired pharmacological properties, e.g. by site-specific payloading with a cytotoxin like MMAF and additional coupling of a half-life extension module like serum albumin⁸⁶. Such a conjugate demonstrated nanomolar potency *in vitro* and a hundred-fold increased serum half-life. This is the first evidence that alternative binding proteins like DARPins are very compatible with the advanced bioorthogonal conjugation chemistries and can be engineered further to optimize the pharmacological properties of the targeting molecules. Importantly, not only the half-life can be engineered but also bispecific binding proteins can be easily designed from such scaffolds, allowing the optimization of drug conjugate performance for tumor targeting⁹⁴.

7. Conclusion and perspective

ADCs combine the specificity of antibodies for tumor-associated antigens to discriminate between normal and malignant cells, and the cytotoxic effect of novel drug agents as payload. The choice of the linker design is crucial for potency and tolerability as it determines stability of the ADC and the site where the drug is released and activated. Despite intensive research in these fields and a growing number of candidates in clinical trials, so far only two ADCs have been granted approval for oncology indications, indicating that there is still ample space for improvements. Clearly, in the parameter space between choice of target, optimal half-life, maximal target-tissue toxicity and minimal systemic toxicity, optima are not so easily found, as all parameters are mutually dependent on each other. Nonetheless, for every molecule, defined conjugation and regiochemistry are important components. For whole antibodies, engineered cysteine sites (THIOMAB technology) and the incorporation of *p*AF with amber suppression technology are two methodologies addressing this problem, each with its own strengths and weaknesses.

For site-specific, stoichiometrically defined and fast drug conjugation, proteins can now be engineered to contain non-native functional groups to perform novel bioorthogonal reactions. Such alternative binding proteins, e.g. DARPins, are very compatible with the novel bioorthogonal conjugation chemistries for payloading and can be engineered for variable half-life, avidity and bispecificity. They hold promise to establish a new generation of functionally improved drug conjugates for cancer therapy as a broad range of desired pharmacological and biophysical functions can be readily introduced into these binding proteins.

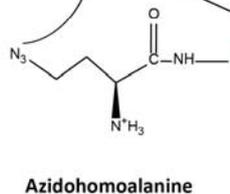
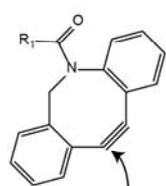
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Abbreviations

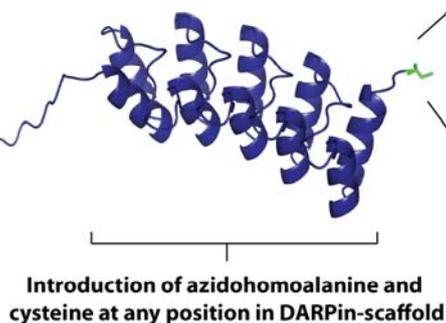
ADC: antibody-drug conjugate; Aha: azidohomoalanine; BCN: bicyclo[6.1.0]nonyne; DAR: drug-antibody ratio; DARPin: Designed Ankyrin Repeat Protein; DBCO: dibenzocyclooctyne; MMAE: monomethyl auristatin E; NHS: N-hydroxysuccinimide; *p*AF: para-acetylphenylalanine; SPAAC: strain-promoted azide-alkyne cycloaddition; TCO: trans-cyclooctene

"Click" Chemistry (SPAAC)



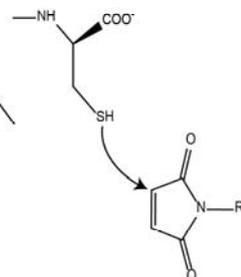
Azidohomoalanine

Double functionalizable DARPin with defined conjugation stoichiometry



Introduction of azidohomoalanine and cysteine at any position in DARPin-scaffold

Cysteine



Thiol Chemistry (Michael Addition)

Figure 1: Double functionalized DARPin (blue) for bioconjugation of effector modules (R1 and R2) at defined positions in the DARPin scaffold.

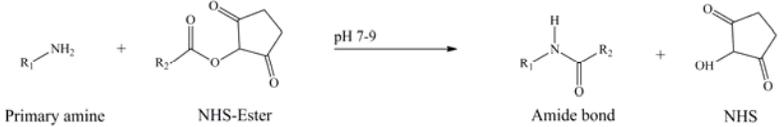
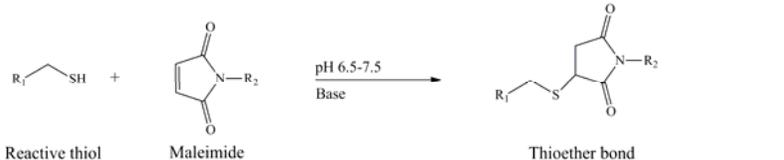
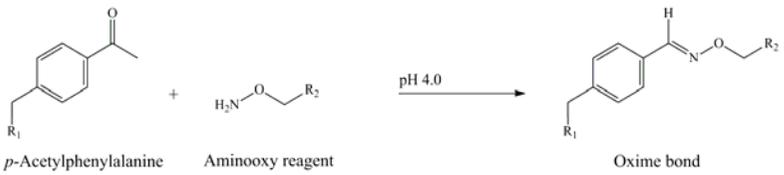
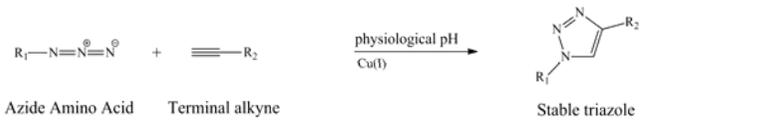
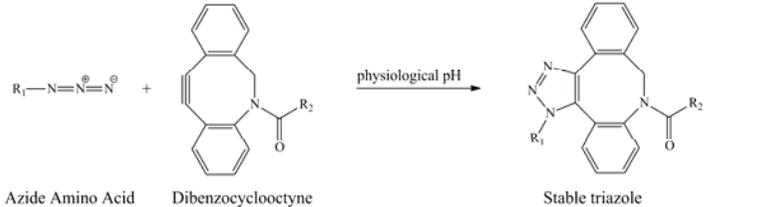
A unique azidohomoalanine (pink) and cysteine (green) can be introduced at any position for bioconjugation by click or thiol chemistry, respectively, for producing stoichiometrically defined DARPin-cytotoxin bioconjugates. The position of azidohomoalanine and cysteine can be moved to any desired position in the DARPin scaffold, and they are shown at the termini merely for clarity. Figure adapted from ⁸⁵.

<i>ADC</i>	<i>Drug</i>	<i>Linker</i>	<i>Coupling reaction</i>	<i>Antigen</i>	<i>Lead indication</i>
<i>Approved</i>					
<i>Brentuximab vedotin (Adcetris®)</i>	MMAE	Valine-citrulline	Cys + maleimide	CD30	HL, ALCL
<i>Ado-trastuzumab emtansine (Kadcyla®)</i>	DM1	Thioether	Lys + NHS (SMCC)	Her2	Breast cancer
<i>Phase III</i>					
<i>Gemtuzumab ozogamicin</i>	Calicheamicin	Hydrazone	Lys + AcBut	CD33	AML
<i>Inotuzumab ozogamicin</i>	Calicheamicin	Hydrazone	Lys + AcBut	CD22	ALL, NHL
<i>Brentuximab vedotin (Adcetris®)</i>	MMAE	Valine-citrulline	Cys + maleimide	CD30	HL, T-cell lymphoma
<i>Ado-trastuzumab emtansine (Kadcyla®)</i>	DM1	Thioether	Lys + NHS (SMCC)	Her2	Gastric cancer, Breast cancer
<i>Phase II</i>					
<i>Glembatumumab vedotin</i>	MMAE	Valine-citrulline	Cys + maleimide	gpNMB	Breast cancer, Melanoma
<i>Pinatuzumab vedotin</i>	MMAE	Valine-citrulline	Cys + maleimide	CD22	NHL
<i>Polatuzumab vedotin</i>	MMAE	Valine-citrulline	Cys + maleimide	CD79b	B-cell lymphoma
<i>SAR3419</i>	DM4	Disulfide	Lys+ NHS (SPDP)	CD19	B-cell lymphoma
<i>Lorvotuzumab mertansine</i>	DM1	Disulfide	Lys + NHS (SPP)	CD56	^a SCLC

Table 1: ADCs FDA-approved or currently in advanced clinical trials (www.clinicaltrials.gov).

AcBut, 4-(4'-acetylphenoxy) butanoic acid; ALCL, Anaplastic Large Cell Lymphoma; ALL, Acute Lymphoblastic Leukemia; AML, Acute Myelogenous Leukemia; HL, Hodgkin's Lymphoma; NHL, Non-Hodgkin Lymphoma; NHS, N-hydroxysuccinimide; SCLC, Small Cell Lung Cancer; SMCC, succinimidyl-4-(N-maleimidomethyl)cyclohexane-1-carboxylate; SPDP, succinimidyl 3-(2-pyridyldithio)propionate; SPP, N-succinimidyl 4-(2-pyridyldithio)pentanoate

^aHalted

<i>Reaction Chemistry</i>	<i>Reaction scheme</i>	<i>Reaction Rate</i>	<i>Conjugation Site in Protein</i>	<i>Incorporation Method</i>
<i>Amine-NHS</i>	 <p>Primary amine + NHS-Ester $\xrightarrow{\text{pH 7-9}}$ Amide bond + NHS</p>	fast	Lysine, terminal amine	Natural
<i>Thiol-Maleimide Michael Addition</i>	 <p>Reactive thiol + Maleimide $\xrightarrow[\text{Base}]{\text{pH 6.5-7.5}}$ Thioether bond</p>	fast	Cysteine	Natural
<i>Oxime Ligation</i>	 <p><i>p</i>-Acetylphenylalanine + Aminoxy reagent $\xrightarrow{\text{pH 4.0}}$ Oxime bond</p>	slow	<i>p</i> -Acetylphenylalanine	Amber suppression
<i>Cycloaddition CuAAC</i>	 <p>Azide Amino Acid + Terminal alkyne $\xrightarrow[\text{Cu(I)}]{\text{physiological pH}}$ Stable triazole</p>	slow	Azidohomoalanine	Methionine - auxotrophic <i>E. coli</i>
<i>Cycloaddition SPAAC</i>	 <p>Azide Amino Acid + Dibenzocyclooctyne $\xrightarrow{\text{physiological pH}}$ Stable triazole</p>	slow	Azidohomoalanine	Methionine - auxotrophic <i>E. coli</i>

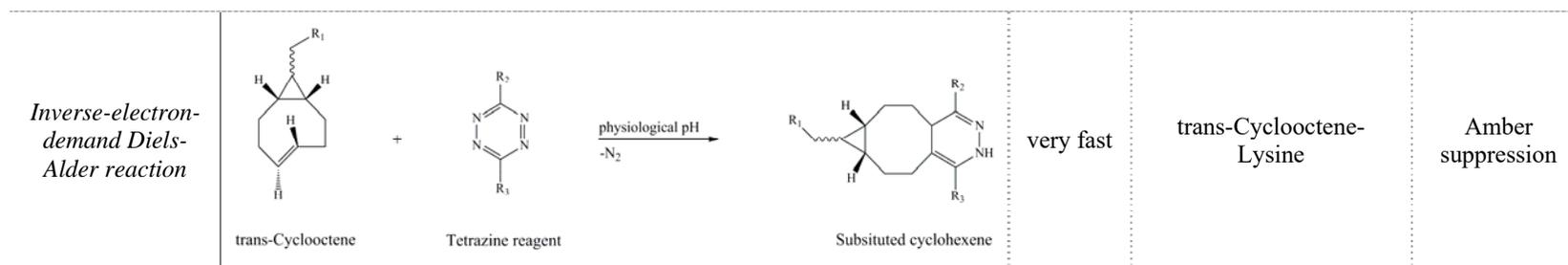


Table 2: Conjugation Chemistries for ADCs.

R₁: protein, e.g., antibody, R₂: drug or linker. Please note that many reactions can be performed with reverse location of functional groups e.g. tetrazine-charged proteins. Here, we list the most common techniques. For reaction details see ^{75, 95}.

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