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Refining the chemical toolbox to be fit for educational and practical purpose for drug discovery in the 21st Century

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Short Title: Refining the chemical toolbox for drug discovery in the 21st Century

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Teaser: Modernisation of theoretical and practical chemistry taught in academia is required for (i) expanding the chemical toolbox and (ii) educating the next generation of drug-hunters.

Refining the chemical toolbox to be fit for educational and practical purpose for drug discovery in the 21st Century

Marco Lolli, Sarah Narramore, Colin W.G. Fishwick and Klaus Pors

Abstract

We live in a time where exploration and generation of new knowledge is occurring on a colossal scale. Medicinal chemists has traditionally played a key role in drug discovery, however the many unmet medical demands in the healthcare sector emphasises the need to evolve the medicinal chemistry discipline. To rise to the challenges in the 21st Century there is a necessity to refine the chemical toolbox for both educational and practical reasons. This article provides suggestions of modern strategies that are beneficial to teaching in academia, but are also important reminders of strategies that potentially can lead to better drugs.

Drug discovery is a complex, time-consuming and a very costly process. In recent years the pharmaceutical industry has been facing increases in the cost of pharmaceutical R&D, driven by the high failure rate of projects and development candidates. Between 2005 and 2010 nine of the largest pharmaceutical companies in the world achieved an average output less than 1 new molecular entity (NME) per company per year despite their combined research expenditure climbing to \$60 billion dollars during this period [1]. Failure in phase 2 clinical trials has been highlighted as a key industry challenge, as only 25% of compounds that currently enter phase 2 successfully progress to full phase 3 clinical studies. It is well-known that a large number of drug candidates fail during the development process due to problems with absorption, distribution, metabolism, excretion or toxicity (ADMET) [2]. For this reason, the evaluation of compounds for their ADMET profile is being carried out at increasingly early stages of the development process. At the same time, strategies have been developed to remove compound structures with undesirable properties when choosing compound sets [3], in order to limit the use of a significant amount of resources to develop candidates which are ultimately unsuccessful [4]. Medicinal chemists play a key role in the drug discovery process [5], however the many unmet medical demands in the healthcare sector emphasise the need to evolve the medicinal chemistry discipline. To rise to the challenges in the 21st Century [6], there is a necessity to refine the chemical toolbox for both educational and practical reasons. Education and training of undergraduate students is, at large, still rooted in the “classical” way of carrying out medicinal chemistry with emphasis on structure-activity relationship (SAR), physico-chemical properties, hit-lead optimisation, solubility and formulation. Paradigms such as ‘Rule of 5’, Ligand Efficiency (LipE), ‘leadlike’ property considerations and perhaps newer additions such as rotatable bonds in the ligand and

polar surface area are taught as fundamental concepts of good medicinal chemistry. However, the question is whether the medicinal chemistry taught in academia globally is truly fit for purpose to solve the grand challenges of treating diseases such as cancer, Parkinson's, and Alzheimer's. The successful completion of the Human Genome Project has opened up exciting new opportunities not only for the medicinal chemist but for other researchers who sees themselves as drug-hunters. If we are going to successfully tap into the wealth of this limitless 'omic' data it will require iterative and synergistic interactions between scientists working at the chemistry/biology interface and the broader research community for years to come. Decoding the information stored in the functional genome, including thousands of predicted gene products, will only be possible with new scientific tools and methods that are fit for purpose [6,7]. Nonetheless, due to the increasingly poor productivity of the pharmaceutical industry as measured by the number of FDA-approved NCEs, there is a need to constantly re-evaluate the drug discovery models we employ. The purpose of this paper is to contribute to the ongoing discussion about modernisation of medicinal chemistry [5,8-15]. As discussed in the following sections, modern approaches including computational chemistry, bioisosterism, scaffold hopping and diversity-oriented synthesis to search for valuable hit compounds in new chemical space are important tools for the medicinal chemists of the future, which can be incorporated into undergraduate and postgraduate teaching with relative ease.

Computer aided hit identification

In the early stages of a drug discovery project computational assistance can be particularly useful in the identification of hits which can form the basis of a medicinal chemistry program. Any target that has structural data available, or even just known

ligands, can be assessed computationally to identify potential hit compounds either using *de novo* design or by using virtual screening (VS) [16,17]. Design approaches that seek to identify hits based on their ability to complement features of a protein structure are called structure-based and approaches that look for hits based on similarity to known inhibitors are called ligand-based (for a simplistic overview, see Figure 1) [18].

Insert Figure 1

Virtual screening

Back in the nineties, *virtual screening* (VS), which is a means of efficiently docking sets of molecular structures to a target protein, emerged as a valuable tool able to guide and focus experimental efforts on smaller, filtered sets of compounds with increased probability of showing the desired biological activity. *Chemical space* is a term widely used in drug discovery to refer to the vast number of theoretically possible molecules. Sets of molecules can be mapped to illustrate the distribution of their properties [19]. VS allows the interrogation of large portions of chemical space without the need to physically possess the molecules in question. In the last 3 years, over 2000 papers have been published which mention the use of VS in applications as diverse as antimalarials [20], cognitive impairment [21] and cancer [22]. VS is becoming increasingly popular due to its ease of use relative to the cost, time and expertise needed to carry out HTS. There are many software packages available for carrying out small molecule docking, several of which are free for academic use, and

as a result, the literature is full of papers describing the results of VS campaigns against a wide variety of targets.

Impressive examples of VS include a strategy by Halland *et. al.* who, very recently, carried out ligand based VS using ROCS [23] to great effect in the search for SGK1 inhibitors [24]. A library of 2 million commercially available structures was screened to find structures similar to known inhibitors of the protein and 78 compounds were selected for biological evaluation of which 7 were active including compound **1**, Figure 2. Library synthesis was then employed to explore SAR around the two most promising hits and a series of highly potent and selective compounds with attractive physico-chemical, ADME and pharmacokinetic (PK) properties was developed.

Recently, Li *et. al.* have reported the use of structure-based VS to identify inhibitors which target the DNA binding region of the human androgen receptor. This is a binding site which had no previously known ligands, but was identified by the group as a promising target for inhibition of the receptor. By performing VS using Glide [25] they were able to identify some compounds with activities in the low micromolar range, and further shape similarity searching within the ZINC database identified even more active compounds which were used as the starting points for a full medicinal chemistry campaign resulting in compound **2** (Figure 2) which exhibited submicromolar activity against the enzyme [26].

***De novo* design**

De novo design can be used to generate entirely novel starting points for synthesis and has the potential to design compounds with very high ligand efficiency. *De novo* design is attractive because it provides the opportunity to sample a much wider area of chemical space than that offered by the contents of a commercial compound library.

However this approach does require a greater investment of chemical resource early in a drug discovery project, as hits generated by the software must be synthesised to establish their activity rather than simply being purchased.

Recently Yule *et al.* reported a series of potent, antibiotic inhibitors of the ATP binding site of DNA gyrase [27]. The fragment connection approach used within SPROUT [28] produced an initial hit molecule, which was synthesised and shown to be active against the enzyme. This hit was then developed into a series of promising inhibitors including compound **3** (Figure 2) that are now being further explored for drug-like potential.

A different approach to structure-based *de novo* design has recently been used by the Baell group at the University of Melbourne in the design of a series of peptidomimetic inhibitors of BCL-XL using the program SYBYL [29]. An unsubstituted benzoyl urea scaffold was identified and then decorated with groups, which were oriented in such a way as to make desired interactions in the enzyme active sites. A thorough SAR investigation produced several inhibitors with low micromolar IC₅₀s including compound **4** (Figure 2).

Ligand-based *de novo* design was recently employed by Rodrigues *et al.* to generate promising anti-angiogenesis compounds, which inhibit the kinase VGFR-2 [30]. They used the program DOGS (design of genuine structures) to identify analogues of a known VGFR-2 inhibitor and synthetic routes to the designed compounds, including compound **5** (Figure 2), which proved to be effective inhibitors of cell proliferation.

Insert Figure 2

Bioisosterism: new ways to access diverse chemical space.

When compound libraries for use in VS and HTS were first being constructed, the focus was mostly on synthesising as many compounds as possible. However, it was soon realised that chemical diversity was a more important aim and recently quality has become the guiding principle [5]. The meaning of 'quality' in this case involves a balance of multiple criteria including structural diversity, bioavailability, permeability, drug-likeness and target focus, among others [31]. In 1997, Lipinski's "Rule of Five" began a trend of focussing drug discovery efforts on confined areas of chemical space likely to contain compounds with pharmaceutically relevant properties. Since then, many related modified or related rules have been proposed [32].

In order to enhance molecular complexity *organic synthesis* was called upon to support VS and HTS to accomplish the role which natural chemodiversity has played traditionally [33] in covering large and novel areas of chemical space. In particular, assistance has come from a traditional, powerful tool used by the medicinal chemist: *bioisosteric replacement* [34]. This approach is often used not only to improve ADME and physico-chemical properties (water solubility, logP, pKa, etc.), but also to increase potency, enhance selectivity and decrease toxicity, or to gain a novel intellectual property (IP) position.

The concept of bioisosterism is based on the notion that single atoms, groups or whole molecules that exhibit similar volume, shape, and/or physicochemical properties can produce broadly similar biological effects. Two functional groups should be called *isosteres* if they share similar physico-chemical properties. When *isosteres* are able to share also the same biological profile they are called *bioisosteres*. Bioisosteres cannot behave in exactly the same manner as the functional group they are intended

to replace and, as a consequence, some bioisosteres might be successful at some targets but not at others. It could be said that while chemistry defines the isosteric similarity between groups, only the biological target can determine the similarity of bioisosteres.

Traditionally, this powerful strategy has been applied to single functional groups. Employed since the 70's by Wermut [35], the proof of the importance of this technology in the modern drug discovery setting is substantiated by the fact that a comprehensive review published by Meanwell in the Journal of Medicinal Chemistry (JMC) in 2011 [36] became the most downloaded JMC article in following years. Quite recently, the replacement of carboxylic acids with suitable bioisosteric surrogates has been reviewed [37]. The carboxylic acid has been much investigated in terms of bioisosteric replacements; this interest can be explained from its frequent presence in pharmacophores resulting in the large number (>450) of carboxylic acid-containing drugs marketed worldwide. Bioisosteres of the α -amino acidic moiety have also been reviewed recently [38]. In this case, bioisosterism of the whole α -amino acid moiety is accomplished with heterocyclic bioisosteres that often display an acidic function.

A new strategy referred to as *scaffold hopping* has matured as a subset of bioisosteric replacement, for discovering structurally novel compounds to explore chemical space [39]. This process, also known as *lead hopping*, typically starts with known active compounds and modifies the central core structure of the molecule to give a novel chemotype [40]. The core may be of direct functional importance in interacting with the protein target or it may provide the necessary scaffolding to allow substitution with functional groups in the appropriate geometric configuration to interact with the target. In other words, scaffold hopping is a useful strategy in drug design to 'jump' into

different areas of chemical space, for example to identify easily synthesisable small molecules that mimic complex natural products. Thus, scaffold hopping represents an attractive strategy to address novelty within confined chemical space, and by consequence achieve favourable intellectual property positions [41]. A classification of scaffold hopping into four major categories, namely heterocycle replacements, ring opening or closure, peptidomimetics, and topology-based hopping, has been recently proposed [40]. Some examples of recently published applications of this technique to oncology related targets are presented below.

Ge *et al.* recently [42] demonstrated scaffold hopping could be applied to the identification of potential anti-tumour agents based on known inhibitors. The approach started by collecting sixteen anti-cancer compounds previously isolated from natural sources (*Clausena vestita*). The sixteen hits, besides sharing the same carbazole alkaloid scaffolds, were found to inhibit cell growth with a pIC₅₀ 3.80-5.37 range. Starting from these structures, the application of a scaffold hopping approach enabled the identification of eight hits, including compound **6** (Figure 2), showing similar anti-tumour activities at the cellular level to the starting compounds but characterised by completely different scaffolds. These represent a valuable starting point for the generation of new lead candidates.

Human *dihydroorotate dehydrogenase* (hDHODH) is a class-2 dihydroorotate dehydrogenase extensively used by proliferating cells. Its inhibition in autoimmune and inflammatory diseases, cancers, and multiple sclerosis is therefore of substantial clinical importance. The strategies employed in the development of DHODH inhibitors have been recently reviewed [43]. Scaffold hopping approaches have recently been applied to generate new lead candidates from known DHODH inhibitors. In the first example [44] a computational method able to design novel hDHODH inhibitors was

developed. After a validation step, 13 novel *h*DHODH inhibitors were designed using a scaffold hopping strategy (e.g. compound **7**, Figure 2). In the second example [45], structural analogies present in two well-known DHODH inhibitors (*Leflunomide* and *Brequinar*) were identified and resulted in the design of a new class of inhibitors based on the 4-hydroxy-1,2,5-oxadiazol-3-yl scaffold (e.g. compound **8**, Figure 2). In Figure 3, the binding mode of compound **8** is compared with the *lead* compound Brequinar.

Insert Figure 3

Diversity-oriented synthesis

The strength of combinatorial chemistry (combiChem) is based on the creation of large populations of molecules, or libraries that can be screened efficiently *en masse* in a short period of time. Whilst the vast amounts of money spent on development of combiChem libraries has not yet resulted in many drug successes, combiChem has spun out many exciting technologies that now occupy a central place in the biotech industry. The mapping of the human genome may have provided a new area of application for combiChem in combination with other HTS methodologies including techniques and instruments developed for DNA microarrays. Indeed, high-density chemical microarrays can now be synthesised *in situ* on glass slides or be printed through covalent linkage or non-specific adsorption to the surface of the solid-support with fully automatic arrays. In conjunction with the “one-bead one-compound” combinatorial library method, chemical microarrays have proven to be very valuable in hit identification and lead optimisation [6,46]. One limitation of combiChem is that

the small molecules developed using this technique do not cover a broad area of chemical space and in recognition of this, diversity-oriented synthesis (DOS) as a relatively new technique for exploring chemical space, is gaining momentum. One of the aims of DOS is to populate undeveloped chemical space by using dependable reactions to generate novel chemical scaffolds. Such scaffolds are designed to be structurally diverse in order to navigate new chemical space, enhancing the possibility of uncovering new biologically active molecules primarily as tools for chemical genetics, but also to provide a new chemical pool for drug discovery [47-51]. Chemical genetics is increasingly providing scientists with a new set of complementary chemical tools to investigate biological systems [52]. Given the emerging limitations of using siRNA to completely suppress target expression as well as off-target effects, there have been calls for highly specific small molecules to be employed as chemical tools to interrogate new biological targets [53]. The constant evolution of chemical techniques and their application to biological systems will inevitably speed up the process of discovering NCEs with improved therapeutic efficacy.

Merging innovation and teaching

So how do we make ends meet? The speed with which we have generated new knowledge, especially at the molecular biology level, in the last part of the 20th Century and in the beginning of the 21st Century has been breath-taking and yet the methodologies we employ in medicinal chemistry remain, in comparison, somewhat pedestrian. Despite over half a century of medicinal chemistry practice that has matured a step at a time into a reliable discipline, there is no doubt that medicinal chemists need to take to their heart innovations in VS, DOS, chem- and bioinformatics, chemical genetics and chemical biology. This is especially the case in light of

estimates that indicate that known chemical space, including public databases and corporate collections contains on the order of 100 million molecules and there may be as many as 10^{60} compounds which would comply with Lipinski's rule of 5 [54]. A more modest estimate of 10^{20} – 10^{24} molecules can be reached if a combination of known fragments are considered [55], but this number is still staggeringly large and in fact it has been suggested that almost all small molecules (>99.9%) have never been synthesised and are still available to be prepared and tested [19]. However, just as much as astronomical "space" is a void, much of chemical space contains nothing of biological interest [56]. Therefore, the drug-hunter needs to be innovative in order to overcome current challenges and boundaries to deliver smarter small molecules that can modernise our healthcare. However, the success in reducing attrition rates and sustaining productivity in an increasingly challenging environment with limited funding in both academia and industry is a challenge of immense magnitude [7]. Accordingly, medicinal chemists and other drug-hunters must have a willingness to constantly refine their knowledge and skill-sets as well as being willing to explore new strategies and paradigms.

Ironically, modernising medicinal chemistry in some ways takes us back to the early stages of the last century, when the great Paul Erlich and colleagues were stepping into new territory, by carrying out pharmacological studies using dyes from the textile industry. Clearly we understand much better where we are heading and we have a lot more experience under our belt, yet we are nowhere near finding a cure for some of the major diseases such as cancer. We are pretty good at using new tools and embracing technologies that allow us to visualise molecular interactions, draw upon previous information and knowledge to predict properties, avoid inefficiencies and

redundancies and also explore new ways in which the experience and expertise can be used to explore scientific boundaries. Paradoxically, however, to meet the healthcare challenges of the 21st Century we may have to, once again, learn how to “work in the dark” to search new areas of chemical space in the hunt for novel drugs. To achieve this, academia and industry must work together and share technical advances, but also share the burden of developing the next generations of drug-hunters. Efforts are already being made to advance education at the undergraduate level. An example of this was reported by Fray et al who reported a study carried out at the University of Nottingham in the UK and GSK [57], which was focussed on the development of a practical medicinal chemistry course, suitable for third-year undergraduates. In the course, the students learned about successfully designing more potent and soluble analogues of a weakly potent, insoluble phosphatidylinositide 3-kinase delta (PI3K δ) inhibitor through compound array design, molecular modelling, screening, data-analysis and the synthesis of target compounds in the laboratory. While this project benefitted from significant industrial support (including lectures, student mentoring and provision of a consumables budget) and is therefore more difficult to implement universally it was a great example of how academia and industry can work together to create a learning environment that embraced conceptual design and innovation in medicinal chemistry.

At the University of Leeds, fourth year undergraduates studying medicinal chemistry and postgraduate masters students studying chemical biology and drug design can attend a computational drug design course, which allows them to gain an insight into structure-based drug design and the use of computational methods. Students explore the active site of abl kinase and use computational docking to investigate possible variations of a known ligand (Imatinib) [58] in a simple virtual SAR investigation. The

final part of the course involves use of SPROUT to carry out *de novo* design looking for novel structures expected to inhibit the enzyme. Students also study medicinal chemistry strategy, biological chemistry and the use of important chemical biology tools.

Concluding remarks

A recent study [59] argued that medicinal chemists ought to pursue innovative goals and balance efficiency and innovation. The entrepreneurial medicinal chemist ought to broaden the discipline to chemical biology while maintaining close feedback from clinical development. The training in innovative thinking and entrepreneurship should be implemented already at the undergraduate level so one of the challenges is to make sure that science we teach at undergraduate and postgraduate level is updated and not outdated. Exploring new regions of chemical space has reinvigorated the hunt for highly specific chemical tools and innovative drugs, expanding many more potential avenues that can be pursued in order to find success. We have, in this article, focussed on computational methods, bioisosterism/scaffold hopping and DOS as these are methodologies often used to develop NCEs while at the same time topics that can easily be implemented in medicinal chemistry and chemical biology courses without a great need for financial support.

In whatever shape or form the drug-hunter comes in, we live in a time where exploration and generation of new knowledge is occurring on a colossal scale; medicinal chemists can draw on an impressive volume of distilled knowledge in order to power through chemical space, but the journey will only be successful if we understand how to make the best use of both traditional and innovative tools. We are

at the beginning of an exciting journey into unknown chemical space hoping to find new inhibitors and druggable targets, which will put us on the path towards cures for the major diseases we have not been able to treat so far.

Insert Figure 4

Bibliography

- 1 Bunnage, M.E. (2011) Getting pharmaceutical R&D back on target. *Nat Chem Biol* 7 (6), 335-339
- 2 Hann, M.M. and Keseru, G.M. (2012) Finding the sweet spot: the role of nature and nurture in medicinal chemistry. *Nat Rev Drug Discov* 11 (5), 355-365
- 3 Baell, J.B. and Holloway, G.A. (2010) New substructure filters for removal of pan assay interference compounds (PAINS) from screening libraries and for their exclusion in bioassays. *J Med Chem* 53 (7), 2719-2740
- 4 Lavecchia, A. and Di Giovanni, C. (2013) Virtual screening strategies in drug discovery: a critical review. *Curr Med Chem* 20 (23), 2839-2860
- 5 Johnstone, C. (2012) Medicinal chemistry matters - a call for discipline in our discipline. *Drug Discov Today* 17 (11-12), 538-543
- 6 Pors, K. (2011) Drug Discovery into the 21st Century. in *Drug Discovery and Development - Present and Future*, edited by Izet M. Kapetanovic (Ed.), ISBN: 978-953-307-615-7, InTech, Available from: <http://www.intechopen.com/articles/show/title/drug-discovery-into-the-21st-century>.
- 7 Pors, K. et al. (2009) The changing landscape of cancer drug discovery: a challenge to the medicinal chemist of tomorrow. *Drug Discov Today* 14 (21-22), 1045-1050
- 8 Satyanarayanajois, S.D. and Hill, R.A. (2011) Medicinal chemistry for 2020. *Future Med Chem* 3 (14), 1765-1786
- 9 Hoffmann, T. and Bishop, C. (2010) The future of discovery chemistry: quo vadis? Academic to industrial-the maturation of medicinal chemistry to chemical biology. *Drug Discov Today* 15 (7-8), 260-264
- 10 Doyle, M.P. (2010) The evolving nature of chemical education: challenges and opportunities. *Future Med Chem* 2 (2), 247-249
- 11 Pitman, S. et al. (2014) Spotlight on medicinal chemistry education. *Future Med Chem* 6 (8), 865-869
- 12 Roughley, S.D. and Jordan, A.M. (2011) The medicinal chemist's toolbox: an analysis of reactions used in the pursuit of drug candidates. *J Med Chem* 54 (10), 3451-3479
- 13 Lombardino, J.G. and Lowe, J.A., 3rd. (2004) The role of the medicinal chemist in drug discovery--then and now. *Nat Rev Drug Discov* 3 (10), 853-862
- 14 Erhardt, P.W. (2002) Medicinal chemistry in the new millennium. A glance into the future. *Pure and Applied Chemistry* 74 (5), 703-785
- 15 MacCoss, M. and Baillie, T.A. (2004) Organic chemistry in drug discovery. *Science* 303 (5665), 1810-1813

- 16 Kutchukian, P.S. and Shakhnovich, E.I. (2010) De novo design: balancing novelty and confined chemical space. *Expert Opinion on Drug Discovery* 5 (8), 789-812
- 17 Schneider, G. (2010) Virtual screening: an endless staircase? *Nat Rev Drug Discov* 9 (4), 273-276
- 18 Ripphausen, P. et al. (2011) State-of-the-art in ligand-based virtual screening. *Drug Discovery Today* 16 (9–10), 372-376
- 19 Reymond, J.L. and Awale, M. (2012) Exploring chemical space for drug discovery using the chemical universe database. *ACS Chem Neurosci* 3 (9), 649-657
- 20 Shah, F. et al. (2012) Computer-Aided Drug Design of Falcipain Inhibitors: Virtual Screening, Structure–Activity Relationships, Hydration Site Thermodynamics, and Reactivity Analysis. *Journal of Chemical Information and Modeling* 52 (3), 696-710
- 21 Mountford, S.J. et al. (2014) Synthesis, Structure–Activity Relationships and Brain Uptake of a Novel Series of Benzopyran Inhibitors of Insulin-Regulated Aminopeptidase. *Journal of Medicinal Chemistry* 57 (4), 1368-1377
- 22 Zheng, C. et al. (2014) Synthesis and Biological Evaluation of Novel Tetrahydro- β -carboline Derivatives as Antitumor Growth and Metastasis Agents through Inhibiting the Transforming Growth Factor- β Signaling Pathway. *Journal of Medicinal Chemistry* 57 (3), 600-612
- 23 Hawkins, P.C. et al. (2007) Comparison of shape-matching and docking as virtual screening tools. *J Med Chem* 50 (1), 74-82
- 24 Halland, N. et al. (2014) Discovery of N-[4-(1H-Pyrazolo[3,4-b]pyrazin-6-yl)-phenyl]-sulfonamides as Highly Active and Selective SGK1 Inhibitors. *ACS Medicinal Chemistry Letters* Epub 23 Oct. DOI: 10.1021/ml5003376
- 25 Halgren, T.A. et al. (2004) Glide: A New Approach for Rapid, Accurate Docking and Scoring. 2. Enrichment Factors in Database Screening. *Journal of Medicinal Chemistry* 47 (7), 1750-1759
- 26 Li, H. et al. (2014) Discovery of Small-Molecule Inhibitors Selectively Targeting the DNA-Binding Domain of the Human Androgen Receptor. *Journal of Medicinal Chemistry* 57 (15), 6458-6467
- 27 Yule, I.A. et al. (2014) Pyridine-3-carboxamide-6-yl-ureas as novel inhibitors of bacterial DNA gyrase: Structure based design, synthesis, SAR and antimicrobial activity. *European Journal of Medicinal Chemistry* 86 (0), 31-38
- 28 Gillet, V. et al. (1993) SPROUT - A PROGRAM FOR STRUCTURE GENERATION. *Journal of Computer-Aided Molecular Design* 7 (2), 127-153
- 29 Brady, R.M. et al. (2014) De-Novo Designed Library of Benzoylureas as Inhibitors of BCL-XL: Synthesis, Structural and Biochemical Characterization. *Journal of Medicinal Chemistry* 57 (4), 1323-1343
- 30 Rodrigues, T. et al. (2013) Steering Target Selectivity and Potency by Fragment-Based De Novo Drug Design. *Angewandte Chemie International Edition* 52 (38), 10006-10009
- 31 Deng, Z.L. et al. (2013) Exploring the biologically relevant chemical space for drug discovery. *J Chem Inf Model* 53 (11), 2820-2828
- 32 Vistoli, G. et al. (2008) Assessing drug-likeness--what are we missing? *Drug Discov Today* 13 (7-8), 285-294
- 33 Hilker, M. (2014) New synthesis: parallels between biodiversity and chemodiversity. *J Chem Ecol* 40 (3), 225-226
- 34 Wermuth, C.G. et al. Bioisosterism. . In *Comprehensive Medicinal Chemistry II Editors-in-Chief: John B. Taylor and David J. Triggle ISBN: 978-0-08-045044-5*.
- 35 Wermuth, C.G. (2008) The Practice of Medicinal Chemistry (3rd Ed).
- 36 Meanwell, N.A. (2011) Synopsis of some recent tactical application of bioisosteres in drug design. *J Med Chem* 54 (8), 2529-2591
- 37 Ballatore, C. et al. (2013) Carboxylic acid (bio)isosteres in drug design. *ChemMedChem* 8 (3), 385-395

- 38 Poulie, C.B. and Bunch, L. (2013) Heterocycles as nonclassical bioisosteres of alpha-amino acids. *ChemMedChem* 8 (2), 205-215
- 39 Brown, N. (2014) Bioisosteres and Scaffold Hopping in Medicinal Chemistry *Mol. Inf.* 33, 458 – 462
- 40 Sun, H. et al. (2012) Classification of scaffold-hopping approaches. *Drug Discov Today* 17 (7-8), 310-324
- 41 Brown, N. (2014) Scaffold Hopping in Medicinal Chemistry. *First Edition. Wiley-VCH Verlag GmbH & Co. KGaA*
- 42 Ge, H. et al. (2014) Scaffold hopping of potential anti-tumor agents by WEGA: a shape-based approach *Med. Chem. Commun. Med. Chem. Commun* 5, 737.
- 43 Munier-Lehmann, H. et al. (2013) On dihydroorotate dehydrogenases and their inhibitors and uses. *J Med Chem* 56 (8), 3148-3167
- 44 Shih, K.-C. et al. (2014) Development of a Human Dihydroorotate Dehydrogenase (hDHODH) Pharma-Similarity Index Approach with Scaffold-Hopping Strategy for the Design of Novel Potential Inhibitors. *PLOS ONE* 9 (2), 1-11
- 45 Lolli, M.L. et al. (2012) New inhibitors of dihydroorotate dehydrogenase (DHODH) based on the 4-hydroxy-1,2,5-oxadiazol-3-yl (hydroxyfurazanyl) scaffold. *Eur J Med Chem* 49, 102-109
- 46 Lam, K.S. and Renil, M. (2002) From combinatorial chemistry to chemical microarray. *Curr Opin Chem Biol* 6 (3), 353-358
- 47 Collins, I. and Jones, A.M. (2014) Diversity-Oriented Synthetic Strategies Applied to Cancer Chemical Biology and Drug Discovery. *Molecules* 19 (11), 17221-17255
- 48 Comer, E. et al. (2014) Diversity-oriented synthesis-facilitated medicinal chemistry: toward the development of novel antimalarial agents. *J Med Chem* 57 (20), 8496-8502
- 49 Koehler, A.N. et al. (2003) Discovery of an inhibitor of a transcription factor using small molecule microarrays and diversity-oriented synthesis. *J Am Chem Soc* 125 (28), 8420-8421
- 50 Kuruvilla, F.G. et al. (2002) Dissecting glucose signalling with diversity-oriented synthesis and small-molecule microarrays. *Nature* 416 (6881), 653-657
- 51 Schreiber, S.L. (2000) Target-oriented and diversity-oriented organic synthesis in drug discovery. *Science* 287 (5460), 1964-1969
- 52 Lehar, J. et al. (2008) Combination chemical genetics. *Nat Chem Biol* 4 (11), 674-681
- 53 Hoelder, S. et al. (2012) Discovery of small molecule cancer drugs: successes, challenges and opportunities. *Mol Oncol* 6 (2), 155-176
- 54 Bohacek, R.S. et al. (1996) The art and practice of structure-based drug design: a molecular modeling perspective. *Med Res Rev* 16 (1), 3-50
- 55 Ertl, P. (2003) Cheminformatics analysis of organic substituents: identification of the most common substituents, calculation of substituent properties, and automatic identification of drug-like bioisosteric groups. *J Chem Inf Comput Sci* 43 (2), 374-380
- 56 Kirkpatrick, P. and Ellis, E. (2004) Chemical space. *Nature* 432, 823
- 57 Fray, M.J. et al. (2013) A practical drug discovery project at the undergraduate level. *Drug Discov Today* 18 (23-24), 1158-1172
- 58 Deininger, M.W. and Druker, B.J. (2003) Specific targeted therapy of chronic myelogenous leukemia with imatinib. *Pharmacol Rev* 55 (3), 401-423
- 59 Hoffmann, T. and Bishop, C. (2010) The future of discovery chemistry: quo vadis? Academic to industrial--the maturation of medicinal chemistry to chemical biology. *Drug Discov Today* 15 (7-8), 260-264

Figure Legends

Figure 1 Different approaches to computer-aided hit identification. A) ligand-based VS, B) structure-based VS C) ligand-based de novo design, D) structure-based de novo design.

Figure 2 Inhibitors designed using the chemical tools described in this paper.

Figure 3 Figure 3: Starting from of well-known DHODH inhibitor Brequinar (A, B), the application of a scaffold hopping strategy resulted in the design of a new class of inhibitors based on the 4-hydroxy-1,2,5-oxadiazol-3-yl scaffold. A comparable lead potency (low nM on rDHODH) by compound **8** (A, C) was obtained by lower binding contacts and, by reflex, with higher ligand efficiency (LE) [45].

Figure 4 Modernisation of theoretical and practical chemistry taught in academia is required for (i) expanding the chemical toolbox and (ii) educating the next generation of drug-hunters.