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Biologically active γ-lactams: synthesis and natural sources

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The γ-lactam moiety is present in a large number of natural and non-natural biologically active compounds. The range of biological activities covered by these compounds is very broad. Functionalized γ-lactams are thus of high interest and have great potential in medicinal chemistry. This review provides a description of the title compounds by focusing on their synthesis, natural sources and biological activities.

1 Introduction

The γ-lactam ring, also known as γ-butyrolactam, pyrrolidin-2-one, azolidin-2-one or 2-oxopyrrolidine, is part of the core structure of a large number of natural and non-natural compounds covering a broad spectrum of biological activities. Accordingly, γ-lactams are of primary interest in medicinal chemistry and many synthetic strategies have been disclosed to access this structural moiety.

The interest in this scaffold started with the observation of the increasing bacterial resistance toward traditional β-lactam antibiotics. To overcome this resistance issue it was necessary to move away from the β-lactam core. Knowing that a suitable activated amide bond is essential for the activity (but not the β-lactam ring), the attention turned naturally to γ-lactams and their analogues, and more specifically to bicyclic γ-lactams such as penem derivatives.

It is in 1986 that the first γ-lactam analogues of penicillins active as antibiotics were reported, independently, by Baldwin et al. and researchers from Eli Lilly.1–4 According to Baldwin, who developed compound A (Fig. 1), the increase in reactivity, and thus the biological activity, of γ-lactam analogues of penems can be accounted for by the delocalization of the lactam nitrogen lone pair into the olefin π system (and stabilization by an electron withdrawing group X).5

Eli Lilly’s group agreed with this assumption and performed additional molecular modeling studies on compounds B.6 The results showed that bicyclic γ-lactams bearing an acylamino...
side chain at C7 instead of C6 and in a β orientation are conformational analogues of β-lactam antibiotics. The decrease in activity resulting from the lower ring strain of the γ-lactam ring compared to β-lactam could be offset by the acylamino side chain.

Due to low but detectable levels of antibacterial activity, these two compounds did not eventually go on the market. Yet, they inspired many chemists to design new biologically active compounds possessing a γ-lactam ring and develop efficient routes toward these compounds. Accordingly, a very large number of pharmaceutically active γ-lactams have since been reported, including antibiotics, anti-inflammatory, cytotoxic and antitumor compounds. Several natural compounds have also been found to possess this structural moiety.

In this review, we focus exclusively on non-aromatic γ-lactam compounds possessing an actual biological activity. In the first part, the different approaches developed for their synthesis are described. Several strategies involve the construction of the γ-lactam heterocycle, through a cyclization or an annulation reaction. The γ-lactam ring can also be formed by the modification of a pre-existing five-membered ring via a reduction or an oxidation process. In the second part of this review, we will discuss about γ-lactams which are non-synthetic but have been extracted from a natural source.

2 Synthesis of the γ-lactam core

Many synthetic approaches have been developed for the preparation of γ-lactam structures. The most intuitive method, and the most widely used, is the cyclization by amide formation between a carboxylic group and an amine or an amine precursor (Fig. 2). The construction of the γ-lactam ring can also be performed by ring-closing an aliphatic amide either by N-alkylation or by C-C bond formation. Beside these cyclization strategies, several (3 + 2) and (4 + 1) cycloaddition/annulation reactions leading to the γ-lactam core have also been devised.

2.1 Cyclization

2.1.1 Via amide bond formation

2.1.1.1 From amino acid derivatives. In 1964, Jenkins et al. elaborated the synthesis of a substituted γ-lactam named doxapram (3) (Scheme 1). Pyrrolidine 1 was in situ transformed into an acyl bromide and subsequent intramolecular addition of the tertiary amine onto this later followed by opening of the pyrrolidine ring by bromide led to pyrrolidinone 2. A single

Fig. 1 First γ-lactam structures showed to possess a biological activity (in A: X = CO2Ph; in B: X = CO2Me, CN).

Fig. 2 Overview of synthetic strategies to build the γ-lactam core (X = leaving group).

Scheme 1 Synthesis of doxapram 3. (a) PBr5, CH2Cl2, reflux, 13 h, 15%; (b) morpholine, EtOH, 90–120 °C, 8 h, 73%.
step, substitution of the bromide atom by morpholine, completed the synthesis of doxapram. This compound is a respiratory stimulant which increases the rate and depth of breathing by activating chemoreceptors the carotids (the activation encourages breathing deeper).\(^{15}\)

Starting from L-glutamic acid, Williams et al. performed, in 1999, the condensation of an amine with a carboxylic acid to access, after reduction, \(\gamma\)-lactam 5 (Scheme 2).\(^{16}\) This was the first step in the total synthesis of (+)-pramanicin 6. Thanks to their work, the stereochemistry of naturally occurring pramanicin could be established. (−)-Pramanicin, the natural compound, exhibits antimicrobial and antibacterial activity (see section 4.1.7).\(^{17}\)

The group of Pérez-Encabo published the synthesis of two aza-analogues of muricatacin using a similar strategy.\(^{18}\) Muricatacin is a natural hydroxy lactone with antiproliferative activity against several human cell lines (K562, HeLa, HL60).\(^{19}\) The two aza-analogue compounds synthesized were the syn and anti 5-(α-hydroxy)-substituted \(\gamma\)-lactams (9) (Scheme 3). In both cases, the quantitative deprotection of the amine group in 7 by hydrogenolysis furnished the free amino-alcohol which then ring-closed in the presence of DCC and 4-pyrrolidinopyridine leading to \(\gamma\)-lactam 8 in a reasonable yield. Final deprotection of the alcohol function allowed obtaining syn and anti 9. Cavé’s group showed that these compounds possess interesting cytotoxic activity on a keratin-forming tumor cell line HeLa (KB cells, \textit{in vitro} assays, \(EC_{50} = 2.7 \text{ to } 7.2 \mu g \text{ mL}^{-1}\)), in the same range as muricatacin itself.

Furthermore, in 2000, Yocum et al. used Ohfune’s methodology\(^{20}\) (reaction of an amine and a base without heating) for producing new matrix metalloproteinase-13-inhibitors (MMP-13 inhibitors) (Scheme 4). In fact, by studying the structure of the known inhibitors and by analyzing the X-ray crystal structure of MMPs (MMP-13 in particular), the authors established that 5 (or 6)-membered peptides could fit the active site. This structure based approach led to compound 12, a potent inhibitor of MMP-13 with an \(IC_{50}\) of 7 nM.\(^{21}\) According to the authors, the conformational rigidity given by the \(\gamma\)-lactam ring could explain the higher selectivity of 12 compared to acyclic compounds. This study should pave the way for the development of inhibitors of other MMPs.

In 2008, Różalski et al. performed an intramolecular condensation between the tert-butylic ester and the primary amine groups of 13 upon heating at reflux of methanol in the presence of sodium carbonate (Scheme 5).\(^{22}\) The aim was to produce analogues of \(\alpha\)-methylene-\(\gamma\)-lactones, known to have a
cytotoxic activity against leukemia cells. Accordingly, the synthesized compounds were evaluated against two human leukemia cell lines (HL-60 and NALM-6). They displayed very low cytotoxic activity: IC\textsubscript{50} of the more active compound (15) is 433 µM (IC\textsubscript{50} of carboplatin, the reference compound, is 0.7 µM). The authors were the first to report that N-analogues of α-methylene-γ-lactones are less efficient. Nevertheless, they described a simple and very diastereoselective method for obtaining phosphoryl-γ-lactams.

A related method involving a thiazolidine and a benzylic ester group via reflux of pyridine was also used by Lee in 1986 (Scheme 6).\textsuperscript{1} The bicyclic lactam 18 designed, as an analogue of penem, showed weak but real antibacterial activity against Gram positive and negative bacteria (data not available).\textsuperscript{1}

γ-Lactam analogues of penems and carbapenems have been subjected to intensive studies at the end of the 80s due to their structural homology with β-lactam antibiotics which act by acylating enzymes involved in bacterial cell wall synthesis. It turned out that they are mostly devoid of activity. Only a few compounds exhibited biological activity; among them, a penem analogue, 21 (Scheme 7).

![Scheme 6](image_url) Synthesis of 18. (a) Pyridine, reflux, 14 h, 45%.

![Scheme 7](image_url) Synthesis of 21. (a) Ra-Ni, EtOH, 60–115 °C, 6 h, 88%.

Boyd et al. investigated the effect of the presence of the 2-amino-thiazol-4-yl-methoximino-acetamido substituent at the alpha position of the carbonyl, known to enhance biological activity in β-lactam systems. Reductive cleavage of pyrazoline 19 with RANEY® nickel gives a diamino ester which cyclizes spontaneously into two diastereoisomers aminopyrrolidinones 20 (Scheme 7).\textsuperscript{2} Compound 21 displayed low but demonstrable activity against three organisms: Minimum Inhibitory Concentration (MIC) values equal 4.0, 8.0, and 32.0 µg ml\textsuperscript{-1} against Streptococcus pyogenes (C0203), S. pneumoniae (PARK) and Staphylococcus aureus (X1.1) respectively. Interestingly, 21 is active against S. aureus X1 but inactive towards its l-form, S. aureus X680. This last result is consistent with a mechanism of action based on the cell wall inhibition type.\textsuperscript{6}

2.1.1.2. From an imine. The group of Decicco reported the formation of a γ-lactam from an imine by a one-pot reduction/cyclization process.\textsuperscript{23} The imine was formed in situ by condensation of 22 and 23 (Scheme 8). After reduction and cyclization, a 1 : 1 mixture of diastereoisomers was obtained. These two isomers could however be easily separated by chromatography. This strategy allowed eventually the synthesis of functionalized γ-lactam 25 which is a potent TNFα converting enzyme (TACE) inhibitor (\(K_{i} = 0.56\) nM). This compound showed a very good selectivity for TACE (from >2000 to >200 fold) relative to ten classes of MMPs.

2.1.1.3. From a nitro group. Barnes group reported, in 2002, the reduction of γ-nitroester 26 into a γ-aminoester which, in situ, cyclizes to give γ-lactam 27, an intermediate in the synthesis of (R)-rolipram (Scheme 9).\textsuperscript{24} RANEY® nickel was chosen to perform the hydrogenation in very good yields and

![Scheme 8](image_url) Synthesis of 25. (a) (i) Zn, AcOH, reflux; (ii) separation, 80% (for both isomers).

![Scheme 9](image_url) Synthesis of (R)-rolipram (28). (a) Ra-Ni/H\textsubscript{2}, H\textsubscript{3}PO\textsubscript{4}, THF, 50 °C, not purified and yield not reported.
no purification was needed at the end of this step. It is interesting to note that in the presence of hydrochloric or triflic acid, the reaction was slower and by-products were formed. The reaction rate was also slowed down when using more than 20 mol% of phosphoric acid (due to the competitive reaction between the acid and nickel). (R)-Rolipram 28, obtained in 92% yield from 26, is a potent inhibitor of phosphodiesterase (PDE) of type IV exhibiting antidepressant and anti-inflammatory activity. 25

Two years later, Costa et al. used a similar approach to obtain γ-lactam 30 from γ-nitroester 29 (Scheme 10). 26 An excess of ammonium formate and a long reaction time are required to reduce entirely the nitro group. This palladium-catalyzed cyclization reaction is a key step in the synthesis of (S)-WEB-1868 (31), a cognitive enhancer, 27 also called a nootropic compound. 28

2.1.2. Intramolecular N-alkylation of an amide. Katayama et al. showed that intramolecular cyclization of γ-bromo-amide 32 in the presence of a strong base affords the corresponding N-methoxy substituted γ-lactam 33 (Scheme 11). 29 Using this strategy, they synthesized 34 which shows in vivo inhibitory activity on adjuvant-induced arthritis (assays on rats). Furthermore, it is well absorbed in the gastrointestinal tract and is less ulcerogenic than other commercially available anti-inflammatory drugs, compound 34 having thus a potent anti-inflammatory activity.

In 1989, Doyle et al. were the first to report a cyclization strategy using the Mitsunobu reaction to obtain a γ-lactam ring. 10 The strategy was used to convert etoposide 35, an anti-tumor lactone marketed as Vepesid®, into the corresponding lactam 38 (Scheme 12). Interestingly, the Mitsunobu reaction of hydrazine derivatives (36) proceeds with an excellent yield whereas direct conversion of lactone 37 into γ-lactam 38 using ammonia remained unsuccessful. γ-Lactam 38 shows a weak activity against P388 leukemia in vivo. The antitumor activity was expressed as % T/C i.e. the percentage of median survival time of the drug-treated group to that of the control group. It equals 185% for a dose of 160 mg kg⁻¹. In comparison, it is 235% for etoposide with a smaller dose of 100 mg kg⁻¹ demonstrating that lactone analogues are more active.

Furthermore, lactam 38 was also evaluated in in vitro cytotoxicity assay against multiple human and murine tumor cell lines and appeared to be more active than etoposide in two cell-lines at an equivalent dose. 31

Another interesting method to access the γ-lactam core from a linear amide is the Swern oxidation of a primary alcohol into an aldehyde which spontaneously undergoes cyclization to form the desired heterocycle. This method was used by Ghosez et al. in 1993 to obtain an intermediate γ-lactam 40 (3:1 mixture cis/trans) and finally furnish 41, an homolog of penems (Scheme 13). 32 Biological evaluations have revealed a weak antibacterial activity (MIC = 320 µg ml⁻¹ against S. aureus) for 41.

In 1998, Naider’s group synthesized a “γ-lactam building block” from acyclic amino acid 42 (Scheme 14). 33 Basic conditions were required to afford the subsequent cyclization into the five membered ring. The strategy was to obtain a constrained analog of Pro-Gly residues in Saccharomyces cerevisiae α-factor. Compound 44 was found to be equally active as the wild one and helped in the understanding of the mechanism of action.
In 2013, Huang et al. performed the intramolecular epoxide ring opening reaction by an amide moiety to access the γ-lactam core (Scheme 15).34 The base (tBuOK) deprotonates the amide which then undergoes S<sub>N</sub>2 type reaction onto the epoxide. The reaction proved to be straightforward and provides the corresponding γ-lactam in high yield. Using this strategy, a single stereoisomer of a natural compound, (−)-clausenamide (47), was obtained in 6 steps. Interestingly, when extracted from nature, clausenamide is found as a racemate (see section 4.2.1). The total synthesis of a single enantiomer was thus really important because the (+)-clausenamide proved to have no activity whereas the (−)-clausenamide has strong potential in the treatment of Alzheimer’s disease (human clinical trials are in progress in China). In fact, it was shown that (−)-clausenamide increased the population spike amplitude (PSA) by 58.1% that is to say was able to induce basal synaptic transmission and thus play a role in learning and memory. The synthesis and the study of other diastereoisomers of clausenamide showed to be also promising antidementia drugs.35 Indeed, they exert a significant neuroprotective effect against β-amyloid in cellular models and potentiate synaptic transmission in the dentate gyrus of rats.

2.1.3. Via C–C bond formation. In 1989, Danishefsky et al. reported the Dieckmann condensation of a β-keto amide ester to access the γ-lactam core of equisetin 49.36 The cyclization takes place quite rapidly (30 min) and provides the desired compound in a quantitative yield. Equisetin is a natural compound showing a broad range of biological activities (see section 4.1.5 for further details) (Scheme 16).

A Dieckmann condensation strategy was also used in 1998 by Corey in the enantioselective synthesis of lactacystin 52, a 20S proteasome inhibitor (see section 4.3.4) (Scheme 17).37 γ-Lactam 51 was obtained as a 1 : 1 mixture of two diastereoisomers. Corey was the first author to report the total synthesis of lactacystin, in 1992.38 He inspired the group of Smith for their total synthesis of this γ-lactam.39,40

In 1993, Ninomiya’s group reported a radical reaction to close the γ-lactam ring (Scheme 18).41 Starting from the N-allyl-N-benzylcinnamamide, they performed a smooth thiy radical addition–cyclization in the presence of a disulphane, furnishing a 1 : 1 mixture of cis/trans diastereoisomers of 54. Nine other steps were necessary to access the racemic natural product anantine 55. The same synthesis was applied to obtain one of its regioisomers, the racemic isoanantine. Both exhibit cytotoxic, antitumor and anti-inflammatory activities (see section 4.2.2).42

Kozikowski et al. used Kagan’s reagent to perform the ring closure of a bioactive compound involved in Protein Kinase C (PKC) modulation.43 Samarium iodide-mediated ring closure of 56 provides γ-lactam 57 as a single diastereoisomer in a good yield (Scheme 19). This step was used in the synthesis of 58 which was developed via a structure-based design study aiming at finding new mimics of indolactam. Indolactam is able to activate PKC, this latter being involved in various biological effects (such as apoptosis and neuronal plasticity).

![Scheme 15](image1)

**Scheme 15** Synthesis of (−)-clausenamide 47. (a) tBuOK (1 eq.), tBuOH, 45 °C, 3 h, 88%; (b) LDA, Davis oxidant, THF, −78 °C, 80%.

![Scheme 16](image2)

**Scheme 16** Synthesis of equisetin 49. (a) NaH, CH₂Cl₂, 0 °C to r.t., 30 min, 100%.

![Scheme 17](image3)

**Scheme 17** Synthesis of lactacystin 52 by Dieckmann condensation. (a) LDA, THF, −78 °C to 0 °C, 2 h, 93%.

![Scheme 18](image4)

**Scheme 18** Synthesis of (±)-anantine 55. (a) h<sub>ν</sub>, (PhS)<sub>2</sub>, PhSH, 71%.

![Scheme 19](image5)

**Scheme 19** Synthesis of 58. (a) SmI<sub>2</sub>, FeCl₃, THF–HMPA, r.t., 91%.
Compound 58 was thus evaluated as an inhibitor of phorbol 12,13-dibutyrate binding from a recombinant PKCa. The K_i value of 296 nM shows that compound 58 is active and could be a promising hit in PKC modulation's area.

Gu et al. reported, in 2001, the enantioselective synthesis of (−)-dysibetaine 61, a natural compound extracted from the marine sponge Dysidea herbacea. The key step of the synthesis involves the formation of the γ-lactam core via intramolecular alkylation of amide 59 which yields pyrrolidinone 60 as a mixture of diastereomers easily separable in the next step of the synthesis (Scheme 20).44 The synthesis of dysibetaine 61 (but also of 3 other stereoisomers) was accomplished in five more steps from 60. Dysibetaine showed an interesting feature because three years earlier, Tagawa’s group found that it was probably active against glutamate receptors in the CNS45 (because of its structural proximity with dysiherbaine non-N-methyl-l-aspartic acid type glutamate receptor agonist) [see section 4.4.2).

Transition metal-catalyzed reactions can also be applied to the formation of a γ-lactam ring.46 For example, Jung et al. reported the rhodium-catalyzed intramolecular C–H insertion of N-benzylated-α-diazo-α-(phenylsulfonyl)acetamide 62 leading to γ-lactam 63 (Scheme 21).47 Reduction of 63 by lithium provided (R)-rolipram 28 which is a selective inhibitor of phosphodiesterase (PDE) type IV, anti-inflammatory agent lithium provided (Scheme 20).44 The synthesis of dysibetaine 61 (because three years earlier, Tagawa’s group found that it was probably active against glutamate receptors in the CNS45 (because of its structural proximity with dysiherbaine non-N-methyl-l-aspartic acid type glutamate receptor agonist) [see section 4.4.2).

Danishefsky et al. showed that cyclization of an imide with a methyl ester in the presence of a base was very effective to access the γ-lactam core of UCS1025A56 (even if a 10 : 1 mixture of diastereoisomers was obtained, Scheme 22). The latter is a natural compound reported to possess antimicrobial and anti-proliferative activities against cancer cell lines (see section 4.1.6).37 More specifically, 66 is believed to act by inhibiting telomerase enzyme and thus could be a possible antitumor agent.

In 2005, Cook et al. reported an interesting intramolecular Michael addition to access the γ-lactam core of 17β-HSD-type 2 inhibitors (Scheme 23).58 This quite atypical strategy was inspired by the work of W. Hartwig59 on his search for 17β-HSD-type 2 inhibitors (IC50 of the best compound is 5.0 µM). In this study, the authors used an intramolecular Michael addition yielding the desired core in a good yield (68%) but a low cis/trans ratio (2 : 1). Cook et al. succeeded in performing the intramolecular 5-endo-dig cyclization of alkyne–amide 67 in the presence of LiHMDS followed by a hydrogenation step, providing 68 in an improved 10 : 1 cis/trans ratio. The authors specified that a purge with argon prior to the basic treatment of the reaction was essential to avoid side-product formation (degradation or oxidation of the desired product). Five further steps allowed obtaining compound 69. Biological assays showed that this latter is a potent 17β-HSD-type 2 inhibitor (with an IC50 of 0.1 µM)60 and that a cis configuration is required for the activity. Inhibition of 17β-HSD-type 2 enzyme (an estradiol degrading enzyme) maintains levels of this hormone in bones, estradiol having a positive effect on the bone mineral density. A novel route is thus opened to treat osteoporosis.
In 2007, Hatakeyama et al. performed a stereoselective cyclization of a substituted amide into a γ-lactam moiety using palladium catalysis (Scheme 24). The aim of this work was to obtain the natural compound neooxazolomycin 72 in an enantiopure form and via a robust synthesis (convergent synthesis). In fact, this natural compound had already been built by the group of De Vita but without any stereocontrol of the bicyclic core. Neooxazolomycin, isolated in 1985 from a broth of Streptomyces sp. by the group of Uemura, is a potent antibacterial and antiviral agent (see section 4.3.5).

Salinosporamide A has been the target of many research groups over the last decade, and several strategies have been disclosed to access its γ-lactam core. This natural compound and its analog cinnabaramide A (see sections 4.3.2 and 4.3.3) are very potent 20S proteasome inhibitors at the sight of their IC_{50} of 1 and 10 nM, respectively (IC_{50} of the potent and selective irreversible proteasome inhibitor lactacystin is 259 nM). Both compounds are therefore promising molecules to treat cancer. Romo’s group synthetic strategy toward these natural compounds consists of a bis-cyclization process which allows the simultaneous construction of γ-lactam and fused β-lactone (Scheme 25). The proposed mechanism for this transformation involves the activation of the carboxylic acid function as pyridone ester (?74) thanks to the Mukaiyama reagent. Transacylation then takes place with 4-pyrrolidinopyridine, followed by deprotonation by Hünig’s base leading to ammonium enolate 76. This latter undergoes aldol-lactonization via 77 to provide the desired skeleton. The main advantage of this synthesis lies in its shortness (despite the fact that racemic compounds are obtained).

Another strategy for preparing (-)-salinosporamide A involves an intramolecular Morita–Baylis–Hillman reaction. Corey et al. used this methodology to transform keto amide ester 81 into γ-lactam 82 (Scheme 26). Two diastereomers are formed in C4 with a diastereomeric ratio in favor of the one leading to (-)-salinosporamide A.

The same group published one year later a new synthesis for this natural compound. Indeed, in order to synthesize a new series of molecules based on the salinosporamide A skeleton, they developed a keto-amide cyclization promoted by a titanium complex as the key step to form the γ-lactam core (Scheme 27). The Kulinkovich reagent (bis-ethoxytitanacyclopropane) promoted the intramolecular carbo-titanation of the acrylamide 83, which leads to heterocycle 84 in an excellent yield and stereoselectivity (only one stereoisomer could be detected).

Another strategy toward γ-lactams is the ring-closing metathesis. Han and Carafa used this methodology in 2011 in their synthesis of 87, a histone deacetylase inhibitor (HDAC), which is an anti-cancer agent (Scheme 28). In their previous work, they developed δ-lactams with good potency in HDAC inhibition. After QSAR studies they however went on with the synthesis of a series of γ-lactams. All the compounds

Scheme 24 Synthesis of neooxazolomycin 72. (a) Pd(OAc)\(_2\) (5 mol%), Ph\(_3\)P (20 mol%), nBu\(_4\)NBr, K\(_2\)CO\(_3\), DMF/H\(_2\)O, 70 °C, 84%.

Scheme 25 Synthesis of (±)-salinosporamide A 79 and (±)-cinnabaramide A 80 by the bis-cyclisation process. (a) Modified Mukaiyama reagent, i-Pr\(_2\)NEt, 4-pyrrolidinopyridine, CH\(_2\)Cl\(_2\), 0 °C, 45%.
were evaluated as HDAC inhibitors and in cancer cell growth inhibition. One of the most active compounds (87, IC<sub>50</sub> = 16.6 nM) shows good inhibition activities on 7 human cancer cell lines and exhibits promising pharmacokinetic characteristics in view of the results obtained with the preADME program. Thanks to the docking study, the authors showed that the γ-lactam core fitted better than the δ-lactam one in the narrow tunnel of the active site.

2.2. Annulation

2.2.1. (4 + 1) annulation. The first application of a (4 + 1) annulation strategy to the synthesis of a biologically active γ-lactam was reported by Dorigotti et al. in 1993. Using an aldehyde as a one-atom unit and an α-aminoamide (glycineamide) as a four-atom unit, they synthesized 1-azabicyclo[3.3.0]octan-3,8-diones 90 upon simple basic refluxing water treatment (Scheme 29). The yield of 90 was however low (23%). Carrying out the reaction in two steps from benzyl protected α-aminoamide 91 and aldehyde 92 was more efficient. Indeed, after deprotection, the obtained corresponding aminal 93 cyclizes to provide the bicyclic lactam 90 in 80% overall yield. Compound 90 is reported to be a potent cognition enhancer which can be seen as a structural analog of oxiracetam, a well-known very potent and safe cognition enhancer. Despite the fact that the mechanism of action is still unknown, the results showed that the γ-lactam core is essential for the biological activity.

In 2004, Dominguez et al. used a (4 + 1) annulation reaction as the first step of the synthesis of N-aryl-γ-lactams. In this case, the γ-lactam core is obtained from the condensation of 3-nitroaniline 94 (one-atom unit) with itaconic acid 95 (four-atom unit) under neat conditions at a high temperature (110 °C) (Scheme 30). A racemate was obtained but the two enantiomers were separated later in the synthesis by the use of Evans' chiral auxiliary. As γ-lactam derivatives seem to mimic a specific dipeptide able to interact with a specific integrin receptor, a series of compounds was prepared and tested as α<sub>v</sub>β<sub>3</sub> integrin antagonists via in vitro competitive electrochemiluminescence binding assays. This SAR study allowed the authors to identify compound 97 as the most selective and potent α<sub>v</sub>β<sub>3</sub> antagonist (K<sub>i</sub> = 0.1 nM, 1R2S), which could open up a new route to osteoporosis treatment. The diastereoisomer 1R2R was not active.

Another interesting strategy is the ring opening–ring closure (RORC) lactamization developed by Bouillon et al. between a saturated lactone and an aminoloquinoline...
derivative (Scheme 31). This (4 + 1) annulation reaction allowed the synthesis of compound 100 which exhibits a good in vitro antimalarial activity against P. falciparum clones (IC50 = 87 nM for 3D7 clones) and no relevant cytotoxicity. This recent work was inspired by the structure of codinaeopsin which showed antimalarial activity (see section 4.1.1).

In 2010, Bandichhor et al. went on to develop a facile and green synthesis of levetiracetam 104. The first step consisted of the condensation of γ-butyrolactone 101 and (S)-amino butanol 102 at high temperatures and under neat conditions to provide the γ-lactam core 103 (Scheme 32). The target molecule was then obtained after two more steps. The synthesis is considered as green not only because of the solvent-free first step but also because no protection/deprotection sequence is used and no side products are generated. Commercially delivered under the name Keppra®, levetiracetam is one of the main anticonvulsant drugs used to treat epilepsy.

Along the same lines, Michel et al. reported, in 2004, the alkylation/cyclization of 4-butanoyl chloride with amino acids to produce a series of levetiracetam analogues (Scheme 33). The synthetic pathway furnishing the most active structure (107; R = nPr) involves the use of a phase-transfer catalyst at low temperatures to avoid racemization. The authors found that this compound is ten times more potent than levetiracetam (assays on mice) and shows significant efficiency in several animal models of epilepsy. Named brivaracetam, it entered phase II clinical trials in 2003 where it appeared to be well tolerated and potent in the treatment of partial seizures. It consequently entered in phase III clinical trials in 2007 in order to evaluate the efficacy, safety and tolerability of adjunctive drugs in patients with partial-onset seizures and uncontrolled partial-onset seizures. UCB announced in January 2015 that brivaracetam would be reviewed in the US and in Europe as an adjunct for the treatment of partial-onset seizures in patients with epilepsy. In November 2015, the European Medicines Agency’s Committee for Medicinal Products for Human Use approved the use of brivaracetam for people with epilepsy. In fact, phase III studies revealed that it significantly reduces the frequency of seizures in patients aged 16 years and older with uncontrolled partial-onset seizures. This molecule will be marketed as Briviact® once finally approved by the European Commission. It is the perfect example of discovery of a new drug by optimization of pharmacodynamics at a molecular target.

In 2011, Patel et al. reported the synthesis of TACE inhibitors possessing a structure close to IK682. The key step of their synthesis consisted of the (4 + 1) annulation between...
protected amino acids and aldehydes under reductive amination conditions to give the desired γ-lactam core of 110 (Scheme 34). After numerous inhibition assays towards TACE and various MMP enzymes, compounds 111 and 112 were found to be potent and selective TACE inhibitors exhibiting an IC50 value of 11 nM and 13 nM respectively. Pharmacokinetics parameters were also analyzed and demonstrated that 112 has a better bioavailability than 111. Inhibition of TACE could offer a promising therapeutic approach for the treatment of inflammatory diseases.

Chibale’s group demonstrated, in 2006, that the Ugi four centers three components reaction (U-4C-3CR) was effective to access the γ-lactam moiety (Scheme 35). Using this strategy, a large library of heterocyclic compounds was created without apparent problems of conversion. Particular efforts were made to purify this huge amount of compounds and finally the “catch and release” protocol gave excellent results. Among all synthesized compounds, 114 and 115 showed particular interest. Indeed, obtained from the reaction between diamine, levulinic acid and tert-butylisocyanide, they show a comparable activity against cultures of P. falciparum parasite to chloroquine, the reference drug used in the treatment of malaria. Indeed, the authors obtained IC50 values of 0.18 μM and 0.27 μM for 114 and 115 respectively, compared to the 0.24 μM of chloroquine.

In 1998, Smith’s medicinal chemists designed, synthesized and evaluated a series of γ-lactam analogs of clavamycin D in order to find new compounds able to enhance the peripheral insulin sensitivity. Their synthetic strategy was based on the reaction between a keto-acid and an amino-alcohol, and allowed obtaining compound 118 in a moderate yield (Scheme 36). In vitro and in vivo tests showed that 118 was the most active compound among those synthesized. The in vitro stimulation of glucose utilization’s test gave a good result with an EC50 value of 6.8 μM. The in vivo test evaluating the hypoglycemic activity revealed that 118 improved significantly glucose metabolism in insulin-resistant animals and diabetic animals. Its potency and efficacy (for one in vivo model) was equivalent to those of troglitazone (launched in 1997 as a potent antidiabetic but withdrawn from the market in 2000 because of hepatotoxicity problems) and metformin, the worldwide reference compound in antidiabetic medication (type 2 diabetes). Compound 118 has a potential valuable effect in the treatment of type 2 diabetes.

2.2.2. (3 + 2) annulation. Carr et al. were the first to report the use of a (3 + 2) strategy for the synthesis of a biologically active γ-lactam. The key reaction of their synthesis consists of a 1,3-dipolar cycloaddition between an enone and an iminium ylide bearing a dithiolane group (Scheme 37); subsequent deprotection of this latter function furnishes the γ-lactam functionality. This methodology appeared to be a fast
regio- and stereoselective method to access this five-membered ring. It was valued in the total synthesis of a natural analgesic compound named cynometrine (see section 4.2.3).\textsuperscript{93}

In 2006 Zhang et al. accomplished the total synthesis of erysothramidine 2 (126), a natural compound bearing a tetracyclic system (see section 4.2.4).\textsuperscript{94} The γ-lactam ring of this compound was built via a (3 + 2) annulation. In this case, the two-atom unit is an (in situ formed) enolate and the three-atom unit is an α-iodo amide (Scheme 38). The erythrinane skeleton of erysothramidine 2 is responsible for its sedative, hypotensive, neuromuscular blocking and CNS activities.\textsuperscript{95}

Later, most (3 + 2) strategies toward γ-lactams turned to the use of an imine group as a two-atom unit. In 2008, Hall et al. reported for instance the synthesis of 130 using a tandem allylation/lactamization to obtain an α-exo-methylene-γ-lactam nucleus from 2-alkoxycarbonyl allylboronate 128 and an imine (Scheme 39).\textsuperscript{96} The reaction is quite general, working with various aromatic and aliphatic imines. The imine allylation reaction is diastereoselective.\textsuperscript{97} Compound 130 was evaluated as a homoserinetransacetylase inhibitor (IC\textsubscript{50} = 140 µM). By comparison, the best known inhibitor (a quinolone) has an IC\textsubscript{50} value of 4.50 µM. α-Methylene-γ-lactams are thus a potential new class of inhibitors.

A similar strategy was used by Roy et al. in their synthesis of 134.\textsuperscript{98} Treatment of a methyl imine (133) with an organozinc reagent (formed in situ from an allyl bromide) allowed generating an α-β-unsaturated γ-lactam intermediate 133 (Scheme 40). Biological testing revealed that compound 134 is an alpha 7 nicotinic acetylcholine receptor agonist (pEC\textsubscript{50} = 8.0). In fact, it displays good selectivity, potency and pharmacokinetic properties.

In 2012, Zhang et al. reported the synthesis of the 2-pyrrolidinone core of 139, a novel antitumor compound, by the (3 + 2) annulation reaction between an imine and a methyl pyruvate derivative (Scheme 41).\textsuperscript{99,100} Compound 139 was evaluated as a novel inhibitor of p53–MDM2 protein–protein interaction and systematically compared with nutlin-3a, one of the most potent inhibitors of the p53–MDM2 interaction. For example, the MDM2 binding affinity value was comparable to the reference nutlin-3a; the in vitro antiproliferative activity against the A549 cell line was better in the case of 139 and no toxicity or drug related death was observed in the nude mice. γ-Lactam inhibitors are thus novel antitumor hits.

Corey et al. used also a (3 + 2) annulation reaction in their total synthesis of (−)-7-methylomuralide (142), which is structurally close to omuralide, a precursor of lactacystin (see section 4.3.4) (Scheme 42).\textsuperscript{101} The key step of their synthesis is

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Scheme 38 Synthesis of erysothramidine 2 126. (a) LDA, THF, −78 °C, 1 h, 87%.

Scheme 39 Synthesis of 130. (a) EtOH, 70 °C, 4 h, 63%; (b) Cul, 4-iodo-biphenyl, N-N’-dimethylhexanediamine, K\textsubscript{2}PO\textsubscript{4}, dioxane, 110 °C, 16 h, 29%.

Scheme 40 Synthesis of 134. (a) (i) Bromide, Zn in THF, r.t., 20 min, (ii) imine, r.t., 3.5 h, 80%. cis/trans ratio = 3/1.

Scheme 41 Synthesis of 139. (a) 1,4-Dioxane, r.t., 12 h, 40%; (b) PPh\textsubscript{3}, DIAD, iPrOH, THF, r.t., 12 h, 41%.

Scheme 42 Synthesis of (−)-methylomuralide 142. (a) LiHMDS, THF, −78 °C, 15 min, 89%.
the condensation, under basic conditions, of the α-amino ester 140 and dimethylmalonyl dichloride to obtain the desired 5-membered ring in a good yield (Scheme 42). Lactacystin is a potent 20S proteasome inhibitor (IC50 value of 259 nM).

Barluenga et al. performed the synthesis of (+) rolipram 28 in 2001 (Scheme 43).35 In this synthesis, compound 145 results from a (3 + 2) cycloaddition involving an azomethine ylide (143) and a menthol derived carbene (144). The cycloadduct formed is then subjected to an ester-hydrolysis–decarboxylation–carbonyl deprotection sequence. More precisely, photochemical oxidation of intermediate 145 and then basic hydrolysis allowed the dithiolane hydrolysis, furnishing N-benzylpyrrolidin-2-one 146 and variable amounts of 147, the N-benzylpyrrolidin-2-one bearing the carboxylic acid at C3.

3. Redox approaches

In this section, we considered the synthesis of biologically active γ-lactam compounds starting from a building block which already includes a five-membered ring (i.e. a masked γ-lactam).

The oxidation of pyrrolidine derivatives is a widely used approach toward the γ-lactam core. Fukuyama’s group applied this strategy to the synthesis of (−)-salinosporamide A 79 (see section 4.3.2).102 Ruthenium mediated oxidation of pyrrolidine 148 at low temperatures allowed these researchers to obtain γ-lactam 149 in a good yield, without oxidation of the cyclic acetal (the electron-withdrawing diester moiety showed to be crucial for chemoselectivity) (Scheme 44).

The same strategy was used by Thomas et al. to access the core of KSM-2690B, a natural compound of the (neo)oxazolomyacin’s family (see section 4.3.5).63,103 Oxidation of the pyrrolidine ring 150 with ruthenium tetroxide in a biphasic media afforded the desired γ-lactam moiety which underwent further oxidation at the benzylic position leading to deprotection of the BOM protecting group (Scheme 45).104 KSM-2690B’s core 152 was obtained in a total of 20 steps. The biologically active compound, bearing five olefins and a terminal oxazole, showed antimicrobial activity against several Gram-positive bacteria and cytotoxic activity against human bladder carcinoma T24 cells.105

Denis et al. developed an efficient synthesis of penmacric acid where the γ-lactam moiety was introduced by oxidation of a proline derivatives.106 The use of ruthenium chloride hydrate yielded the fully protected pyroglutamic acid derivatives 154 as a separable 1 : 1 mixture of diastereoisomers (Scheme 46). Two more steps provided the target molecule, penmacric acid 155, which is a natural biologically active compound (see section 4.2.6). This latter finds applications in food or as an anti-inflammatory agent.108

In 2004, Hatakeyama’s group revisited the (+)-lactacystin synthesis performed by Corey (see section 2.1.3). The authors developed a new and concise strategy toward this natural product (see section 4.3.4) via Kang’s intermediate (157) (Scheme 47).109 The γ-lactam moiety was introduced by ox-
Deoxygenation of pyrrolidinones can be another strategy to access the γ-lactam core. Indeed, Yamashita’s group accomplished the first enantioselective synthesis of (S)-nebracetam 166, a nootropic compound, by deoxygenation of 164 (Scheme 49).118 Subsequent reduction by hydrogenation in the presence of Pd/C resulted in (S)-nebracetam. This compound is known to enhance cholinergic neurotransmission and to reduce dopamine and serotonin uptake.119

4. Natural compounds containing a γ-lactam moiety

Nature has always been an excellent source of pharmaceutical agents: natural compounds can be directly used such as in traditional medicine or inspire chemists in the total or semi-synthesis of analogues with improved biological properties. As we will discuss below, γ-lactam is a key structural feature in a large number of biologically active natural compounds.

The diversity of natural sources of γ-lactam is reflective of the spectrum of biological activities displayed. In fact, this motif can be found in organisms such as bacteria, fungi, plants or even animals. Accordingly, structural features of natural γ-lactams are also wide.

Some specific structural motifs are nonetheless found in many natural γ-lactams suggesting common biochemical pathways. However, very little is reported on the biosynthesis of γ-lactams.120–122 But one can conjecture that glutamic acid, glutathione,121 proline and γ-aminobutyric acid (GABA)123 are the main precursor compounds of γ-lactams in living cells.

In this section we will discuss natural γ-lactam compounds, selected on the basis of their frequency of occurrence in the literature and of data availability, classified according to their origin.

4.1. γ-Lactams from fungi

Among fungal bioactive metabolites containing γ-lactams (Fig. 3), a large proportion of them is based on a decalin motif suggesting a common origin; the polyketide (PKS) non-ribosomal peptide synthase (NRPS) pathway being often quoted.124,125

4.1.1. Codinaeopsin and ascosali pyrrolidinone A. Codinaeopsin and ascosali pyrrolidinone A have a very closely related structure built around a decalin core and a γ-lactam ring (see Fig. 3). Both are active against P. falciparum and thus have an antimalarial activity. The latter was isolated by Osterhage et al. in 2000 from Ascochyta salicornae, a marine fungus and exhibits an IC50 value of 1.72 µM (NF54 strain).126
Furthermore, it inhibits tyrosine kinase p53. It is worth noting that its development as a therapeutic tool will not go further because of its cytotoxicity (effect on rat skeletal muscle myoblast cells). Codinaeopsin\textsuperscript{127} (stereochemistry at C2 is arbitrary) was discovered later, in 2008, in a fungal extract of a tree (Vochysia guatemalensis). Thanks to a high output screening, Kontnik et al. found that it is active against the 3D7 strain of P. falciparum with an IC\textsubscript{50} value of 4.7 µM.

4.1.2. Oteromycin. Isolated from fungus strains MF5810 and MF5811, oteromycin was subjected to a biological testing in 1991. Singh et al. found that it was a novel antagonist of the endothelin receptor type B (ET\textsubscript{B} implicated in vasoconstriction and vasodilatation) with an IC\textsubscript{50} value of 2.5 µM.\textsuperscript{128} In addition, the team of Hazuda discovered its activity as a HIV-1 integrase inhibitor.\textsuperscript{129} The mode of action has however yet to be identified.

4.1.3. ZG-1494 alpha and talaroconvolutin. Thanks to Piggott’s screening program aiming at developing new PAF acetyltransferase inhibitors, the \textit{trans} decalin derivative ZG-1494\textsubscript{a} has been showed to have an IC\textsubscript{50} of 40 µM.\textsuperscript{130,131} Binding assays for PAF, histamine and glucocorticoid receptor binding indicated a promising anti-inflammatory activity (IC\textsubscript{50} = 3 µM). This natural compound has been extracted from a culture broth of \textit{Penicillium rubrum}.

On the other hand, talaroconvolutin B, extracted from \textit{Talaromyces convolutes} (fungus present on barley grains) by Suzuki et al., exhibits antifungal activity against \textit{A. fumigatus}, \textit{A. niger}, and \textit{C. albicans} (between 9 and 15 µg of organisms per disk; using amphotericin as a positive control).\textsuperscript{132} Because the stereochemistry at C5 and C26 has not been determined, talaroconvolutin B and ZG-1494 alpha may be stereoisomers at either position or both.\textsuperscript{130}

\textbf{Fig. 3} Structure of naturally occurring γ-lactams derived from fungi.
4.1.4. Cryptocin. Cryptocin, a tetramic acid derived from the endophytic fungus Cryptosporiopsis cf. quercina, is inactive against human pathogenic fungi but active against numerous plant pathogenic ones (MIC values below 1 µg ml$^{-1}$).\textsuperscript{133} Interestingly, Pyricularia oryzae, responsible for rice blast (one of the most economically important plant pathogenic fungi in the world) is particularly sensitive (MIC = 0.39 µg ml$^{-1}$), making cryptocin a serious candidate for fungicide development.

4.1.5. Equisetin. Discovered in 1974, equisetin was isolated from the fungus Fusarium pallidoseorum. Its chemical structure was identified by Laugal\textsuperscript{134} in 1979 and completely characterized in 1989 by Lynn.\textsuperscript{135} This natural compound shows a very broad range of biological activities.\textsuperscript{136} At first it was known as an antibiotic: it is active against Staphylococcus aureus and erythraea (with respective MIC < 1.25 µg and <2.5 µg), as well as against Bacillus subtilis. Then, other significant activities were discovered such as cytotoxic\textsuperscript{137} and phytotoxic activities.\textsuperscript{138} It is also a potent inhibitor of mitochondrial ATPases and HIV-integrase (IC$_{50}$ values between 7 and 20 µM).\textsuperscript{129}

4.1.6. UCS 1025 A. trans-Decalin UCS 1025 A was isolated from the fungus Acremonium sp. by West et al. It proved to be an antitumor antibiotic on various cell lines (IC$_{50}$ = 21 to 58 µM) as well as a telomerase inhibitor\textsuperscript{124,130,132} making it a potential chemotherapeutic agent. The structure of UCS 1025 A (Fig. 3) was elucidated by NMR and crystallographic studies.\textsuperscript{57} Finally, its total synthesis was reported by Danishefsky in 2005 (see section 2.1.3).

4.1.7. (−)-Pramanicin. Pramanicin is a natural γ-lactam isolated from fungi which do not possess a decalin core. It was extracted and isolated in 1994 by Schwartz et al. from a lactose-containing liquid fermentation (or a corn-based solid) of a sterile fungus growing in grass.\textsuperscript{17} Its stereochemistry was determined by Barrett five years later, in 1999.\textsuperscript{16} MIC tests revealed that pramanicin has a good antimicrobial activity against Candida parapsilosis (MIC = 4 µM), and Cryptococcus neoformans (MIC = 0.062 µM) and also a good antibacterial activity against Bacillus subtilis (MIC = 4 µM).

4.1.8. Fusarin C. Fusarin C is a polyketide produced mainly by the entomopathogenic fungus Metarhizium anisopliae. Its chemical structure was elucidated in 1984 and consists of a polyenic chromophore with a substituted 2-pyrrolidone (see Fig. 3).\textsuperscript{139}

In addition, its biological activities are wide and also opposed. For example, it not only stimulates human breast adenocarcinoma MCF-7 cell line growth but also decreases the viability of colorectal cancer Caco 2 human cells (IC$_{50}$ = 5.6 µM).\textsuperscript{140,141} These opposite effects could be due to the presence of alpha and beta estrogen receptors in those cell lines. In fact, fusarin C is an estrogenic agonist. From 20 µM, cells are inhibited with an IC$_{50}$ value of 46.8 µM but above 20 µM and up to 100 nM, there is an induction.

Another natural analogue (with Z olefins) called NG-391 exhibits also mutagenic properties.\textsuperscript{142}

4.1.9. Epolactaene. Isolated from a fungal strain of a marine sediment in Japan (Penicillum sp.), epolactaene possesses several biological activities. In particular, it is known as a neurotogenic compound and apoptosis inducer.\textsuperscript{143} It induces neurite outgrowth in human neuroblastoma SH-SY5Y cells, which lack significant TRK family mRNA. It constitutes also a rare example of a natural molecule able to bind and inhibit Hsp60 chaperone activity, the latter playing an important role in the folding, translocated and stress denatured proteins.\textsuperscript{144}

The diastereoselective total synthesis of epolactaene was accomplished in 2002.\textsuperscript{145} Recently, Kuramochi reported disulfide formation via reactions of epolactaene with several thiols.\textsuperscript{146} Given the crucial role of disulfide bridges in stabilizing protein structures and hence in protein function, epolactaene could be a promising new drug.

4.1.10. Azaspirene. Azaspirene was isolated in 2002 from the fungus Nostocorysa sp. and is composed of a highly oxygenated azaspirocyclic system and two hydroxyl groups at C8 and C9 positions. Its total synthesis was performed by Hayashi and co-workers in 2002.\textsuperscript{147}

Azaspirene is an angiogenesis inhibitor candidate. In fact, it was shown to inhibit the endothelial migration induced by the vascular endothelial growth factor (ED$_{100}$ = 27.1 µM).\textsuperscript{148}

Besides, azaspirene shares the same core as psuetorin A (IGE inhibitor production)\textsuperscript{149} and synerazol (antifungal and antibiotic).\textsuperscript{150} Based on genome sequencing and feeding experiments, Turner et al. showed that the biosynthesis of these γ-lactams starts from phenylalanine in the human pathogen Aspergillus fumigatus.\textsuperscript{140}

4.1.11. Pyrrocidine A. In 2002, the team of He elucidated the chemical structure of pyrrocidine A, extracted and isolated from the fungal endophyte Acremonium zeae.\textsuperscript{151} This compound exhibits a unique 13-membered macrocycle containing phenyl, ether, ketone and pyrrolidinone function patterns (see Fig. 3). Displaying MIC values of 0.25–2 µg ml$^{-1}$ against Staphylococcus aureus (including two resistant strains), it is a potent antibiotic towards Gram-positive bacteria. This work was pursued in 2008 by the group of Wicklow, working in the field of agrochemistry,\textsuperscript{152} in which pyrrocidine A was utilized against maize pathogen with testing on different strains. The most sensitive are S. maydis, F. graminearum, and C. michiganense subsp. nebraskaense, each of which is a seed-borne pathogen responsible for severe seedling blights and vascular wilts of maize.

4.1.12. PI-091. Taicho Pharmaceutical Co. isolated PI-091 from Paecilomyces sp. F-3430, during a screening aiming at finding new natural platelet aggregation inhibitors. They found that it exhibits arachidonic acid-induced platelet aggregation-inhibitory activity in rabbits with an IC$_{50}$ value equal to 120 µM.\textsuperscript{153} The total synthesis of PI-091 was performed in 1996 and furnished this latter as found in nature, i.e. as a 1:1 diastereoisomeric mixture at the γ-ketal carbon.\textsuperscript{154}

4.2. γ-Lactams from plants

4.2.1. Racemic clausenamide. Clausenamide (Fig. 4) was isolated from a traditional Chinese plant called Clausena lanisum. Although it was isolated as a racemic mixture, only (−)-clausenamide shows biological activities: it improves
learning and memory capacities in amnesia animal models (enhancing synaptic transmission) by enabling the CaMKII α-CREB signal pathway activation via intracellular calcium release.155,156

Based on these improving cognition and anti-Alzheimer’s disease pathogenesis properties,157 clinical trials of (−)-claussenamide for Alzheimer’s disease patients started in China and it entered in phase II in 2015.

4.2.2. Anantin and isoanantin. Anantin and isoanantin belong to the very small family of natural α-methylene-γ-lactams. They were isolated from the leaves of an African plant named Cynometra which was traditionally used to treat cough and pain.158 Both compounds, like most α-methylene-γ-lactams, exhibit cytotoxic, antitumor and anti-inflammatory activities.42

4.2.3. Cynometrine. The γ-lactam alkaloid cynometrine was found in the stem bark of Cynometra hankei161 which is used in traditional African medicine as an antitussive and analgesic (for dental pain and rheumatism).159 Cynometrine belongs to the same family as anantin and isoanantin. Other alkaloids were discovered at the same time: isocynometrine and isonaritine.158

4.2.4. Flavan-3-ol derivatives. 6-(2-Pyrrolidinone-5-yl)(−) epicatechin and its regioisomer with the γ-lactam substituent in position 8, possessing a flavan-3-ol feature, were isolated in 1991 from the roots of Actinidia arguta, an Asian fruit.160 These compounds were tested as an inhibitor of the formation of advanced glycation end products (AGEs) which are over-produced in diabetes. Actually, in vitro tests revealed that these flavan-3-ol derivatives are more potent (IC50 values are 36 μM and 48 μM, respectively) than the glycation inhibitor taken as a reference, aminoguanidine (IC50 = 961 μM).

4.2.5. Erysothramidine 2. Erysothramidine 2 belongs to a class of structurally diverse products isolated from tropical and sub-tropical Erythrina genus plants, used in indigenous medicines. These alkaloids possess a wide range of biological activities including anticonvulsive, sedative, and hypnotic properties.95 Recently, Wink et al. reported it as a neuromuscular blocking agent.161

4.2.6. Penmacric acid. Penmacric acid was isolated by two independent teams162,163 in 1975 from Pentaclethra macrophylla, an African leguminous tree. It has an interesting structure composed of a pyroglutamic acid linked to a glycine via a carbon–carbon bond. This natural compound could find applications as an anti-inflammatory agent, knowing that the extracts of the plant show significant anti-inflammatory activity against acute inflammation108 (78% inhibition of oedema in rat hind paw, 3 h after the administration). It could also find application in food, by being a potential nutritive component in cereal mixture based food.107

4.2.7. Stemoamide. This alkaloid was isolated in 1992 from Stemona tuberosa Lour, a Chinese traditional medicine also called “wild asparagus” used as an anticough agent and also for the treatment of respiratory diseases such as asthma and tuberculosis.164 This explains why extracts of Stemona tuberosa are employed in China and Japan in traditional medicine in the case of respiratory disorders or helminth infection.165,166

4.2.8. Pukeleimide E. Pukeleimide E is an α-methylene-γ-lactam which was isolated from a marine blue green alga named Lyngbya majuscula.42 As other α-methylene-γ-lactams, it is a cytotoxic agent but is about ten times less toxic than the corresponding lactone. It also shows activity against Mycobacterium smegmatis and Streptococcus pyogenes.167

4.3. γ-Lactams from bacteria sources

4.3.1. Lajollamycin. Lajollamycin was isolated from sediments found in the US: the marine actinomycete Streptomyces nodosus (Fig. 5).168 This nitro-tetraene-spiro-β-lactone-γ-lactam was evaluated as an antimicrobial agent against a variety of bacteria (both drug sensitive and resistant micro-organisms).168 The MIC values ranged from 1.5 to 20 μM demonstrating a good antibiotic effect. Furthermore, lajollamycin inhibited murine melanoma’s growth with an EC50 value of 9.6 μM (B16-F10 cell line).

4.3.2. Salinosporamide A. Salinosporamide A bears a quite unusual γ-lactam-β-lactone core (see Fig. 5). It was isolated from a marine bacterium, Salinispora tropica, by Fenical et al.169,170 Due to its structural similarity with the proteasome inhibitor omuralide (see section 4.3.4), it was directly tested as a 20S proteasome inhibitor, showing a very promising activity. In fact, it exhibits an IC50 value of 1.3 nM by inhibiting the proteasomal chymotrypsin-like proteolytic activity in a 20S purified proteasome. This result suggests that it is 35
times more potent than omuralide. It was showed to be also very active against one colon cancer cell line (HCT-116) in the range of 10 nM (in vitro assays). Furthermore, salinosporamide A is found to inhibit in a potent and very selective manner the growth of a broad range of NCI’s 60 cell lines. For example, it is active against NCI-H226 non-small cell lung cancer, SF-539 CNS cancer, SK-MEL-28 melanoma, and MDA-MB-435 breast cancer with GI50 values <10 nM. It is currently in the phase I clinical trial for the treatment of cancer. Many groups reported the stereoselective synthesis of this compound (see sections 2 and 3)66,102,172 allowing for interesting SAR studies.173

4.3.3. Cinnabaramide A. Cinnabaramide A was isolated from a soil bacteria strain (Streptomyces) and has a structure closely related to salinosporamide A. It also shares its biological activities.174 Indeed, it is a potent and selective inhibitor of 20S proteasome (IC50 = 1 nM) and is very active against HCT-116 cell lines. Nevertheless, cinnabaramide A did not show activity against trypsin or chymotrypsin up to 100 µM.

4.3.4. Lactacystin. Lactacystin was isolated from a Streptomyces strain, characterized and crystallized by Omura et al. in 1991.111 Several total syntheses of this natural compound were reported (see sections 2.1.3 and 3).37,39,109,110,175 Lactacystin is a cell-permeable and irreversible 20S proteasome inhibitor (IC50 = 259 nM); this latter being called the “multicatalytic proteinase complex” regulating intracellular protein degradation (removal of damaged/mutated proteins, or proteins involved in cell growth and metabolism for example).175

Interestingly, Dick showed, in 1996, that lactacystin hydrolyzes in aqueous solution into clasto-lactacystin β-lactone (known as omuralide; Scheme 50) and finally into a dihydroxy acid.176 The thiol ester function is indeed reactive enough to allow spontaneous conversion to the β-lactone. It has in fact been proved that omuralide is the sole inhibitory species. The inhibitory mechanism is believed to involve covalent binding to the active site N-terminal threonine residue in some of the β-subunits of the proteasome.

4.3.5. Neooxazolomycin. Neooxazolomycin is a biologically active natural product featuring a fused γ-lactam-γ-lactone core (see Fig. 5). It was isolated from several strains of Streptomyces sp., in 1985, and showed a strong in vivo antitumor activity177 as well as antiviral activities against influenza, herpes simplex type I and vaccinia.178 Its original structure inspired many chemists in developing total or a part of its synthesis (see section 2.1.3).61,62,179

5. Conclusion

The interest in γ-lactams originates from its analogy to the β-lactam core. This review clearly demonstrates that nowadays the interest in γ-lactams is well beyond their analogy with their β-lactam analogues. The γ-lactam motif was indeed found in many natural compounds from bacteria, plants, fungi or even animal sources, covering a large variety of structures and biological activities. Several non-natural γ-lactam compounds have also been developed and shown to possess interesting pharmacological properties.

Many synthetic approaches have been developed for the preparation of γ-lactam structures. The most widely used
methodology involves the cyclization by amide formation but other ring-closing strategies, by N-alkylation or C–C bond formation, have been reported. In recent years, a series of \( (3+2) \) and \( (4+1) \) annulation reactions were also developed to access the \( \gamma \)-lactam core in a more convergent manner. These synthetic methodologies are very important to fully exploit the potential of this scaffold in medicinal chemistry. Several challenges are however likely to be addressed in the future development of new efficient synthesis of \( \gamma \)-lactams. For example, although a limited number of stereoselective syntheses have been reported, developments of general enantioselective catalytic methodologies remain highly desirable.

\( \gamma \)-Lactams thus represent an important class of compounds both from a synthetic and biological point of view and one can expect an increase in the number of drugs on the market containing a \( \gamma \)-lactam core in the next few years.

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**Notes and references**

8. It is important to mention that the \( \gamma \)-lactam motif present in biologically active compounds is not always the pharmacophore. In the examples selected in this review the \( \gamma \)-lactam subunit plays however in one way or another an important role in the activity.
For a review gathering the different synthesis of salinosporamide A see: T. A. M. Gulder and B. S. Moore, Angew. Chem., Int. Ed., 2010, 49, 9346–9367.

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