Overcoming chemical challenges in the solid-phase synthesis of high-purity GnRH antagonist Degarelix. Part 2.

Journal:	*Organic Process Research & Development*
Manuscript ID	op-2019-00540c.R1
Manuscript Type:	Full Paper
Date Submitted by the Author:	n/a
Complete List of Authors:	Guryanov, Ivan; St. Petersburg State University, Institute of Chemistry Orlandin, Andrea; Fresenius Kabi iPSUM Srl Viola, Angelo; Fresenius Kabi iPSUM Srl Biondi, Barbara; C. N. R., Institute of Biomolecular Chemistry Formaggio, Fernando; University of Padova, Department of Chemistry Ricci, Antonio; Fresenius Kabi iPSUM Srl Cabri, Walter; Fresenius Kabi iPSUM Srl

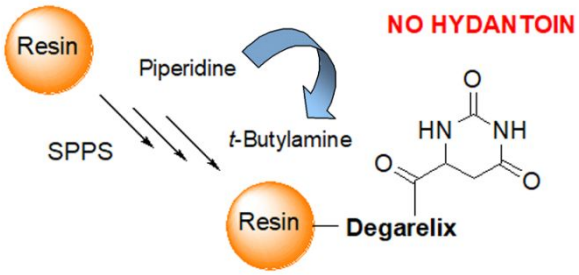
Overcoming Chemical Challenges in the Solid-Phase Synthesis of High-Purity GnRH Antagonist Degarelix. Part 2.

Ivan Guryanov,[*,‡,§,ǁ] Andrea Orlandin,[‡] Angelo Viola,[‡] Barbara Biondi,[§] Fernando Formaggio,[§] Antonio Ricci,[*,‡] and Walter Cabri[‡]

[‡]*Fresenius Kabi iPSUM Srl, via San Leonardo 23, Villadose (RO), 45010 Italy*

[§]*ICB, Padova Unit, CNR, Department of Chemistry, University of Padova, Padova, via Marzolo 1, 35131 Italy*

[ǁ]*St. Petersburg State University, Institute of Chemistry, St. Petersburg, Peterhof, Universitetskij pr. 26, 198504 Russia*


Resin
Piperidine
NO HYDANTOIN
SPPS
t-Butylamine
HN
NH
O
O
O
Resin
Degarelix

ABSTRACT

The hydrolysis and rearrangement of the dihydroorotic (Hor) residue in the presence of bases, leading to the formation of the hydantoin (Hyd) impurity, represents one of the major problems in the manufacturing of the gonadotropin-releasing hormone antagonist Degarelix. In the attempt to find efficient strategies to overcome this problem, we carried out a screening of organic bases in order to select those which afforded both the rapid Fmoc deprotection during solid-phase synthesis and the absence of this peculiar rearrangement. Among the bases tested only *tert*-butylamine did not affect peptide molecule and was able to fast Fmoc removal. The use of *tert*-butylamine for the synthesis of Degarelix led to the product with excellent purity and yield without a detectable amount of the hydantoin impurity. Thus, we showed that *tert*-butylamine can be a suitable alternative to piperidine for industrial scale production of Degarelix or of other Hor-containing peptide pharmaceuticals.

Keywords: Degarelix, dihydroorotic acid, Fmoc deprotection, peptide

INTRODUCTION

Degarelix is a synthetic peptide antagonist of gonadotropin-releasing hormone, which was shown to be efficient for the treatment of advanced prostate cancer.[1-3] The peptide sequence of Degarelix contains several non-proteinogenic amino acids with particular properties, which determine the pharmacological action of this drug (Figure 1).[4,5]

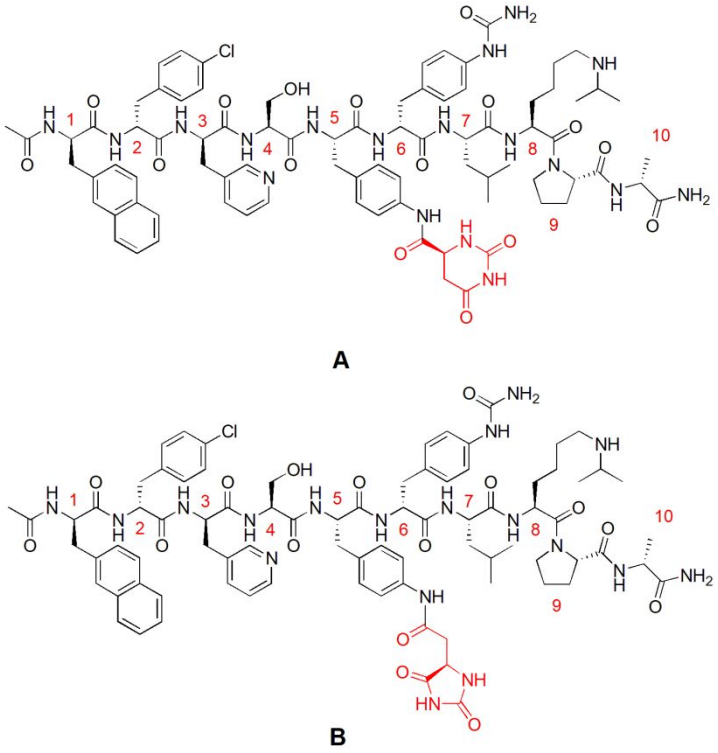


Figure 1. Chemical structures of Degarelix (A) and hydantoin isomer (B) (Hor moiety and the corresponding hydantoin are evidenced in red).

In particular, the presence of the dihydroorotic moiety (Hor) in the side chain of one of the amino acids makes the manufacturing of this peptide rather challenging. Indeed, the Hor group is highly prone to the hydrolysis and rearrangement to the hydantoin (Hyd) structure in the presence of bases and water.[6,7] Due to the high similarity to the parent product, this impurity, poses serious difficulties to the Downstream process (purification), forcing the manufacturers to dramatically reduce the window of the recovery during the preparative HPLC. Similarly, the detection and quantification of this impurity in the purified Degarelix API (active pharmaceutical

ingredient) results to be a complex task even with the most efficient equipment currently available, such as the ultra performance liquid chromatography (UPLC). For all these reasons, the presence in the crude peptide of hydantoin isomer drastically reduces the yield and productivity of Degarelix manufacturing process and compromises the quality of the API launched in the market as well.

Because of the presence of several non-proteinogenic amino acids, Degarelix can be produced only by chemical approaches, such as Boc or, more frequently, Fmoc solid-phase peptide synthesis (SPPS). The conventional methodologies of Fmoc-based SPPS include repetitive Fmoc-deprotection cycles with the organic bases. In this case, piperidine is widely accepted as a reagent of the first choice. Unfortunately, these repetitive basic treatments can induce the Hor-to-Hydantoin rearrangement, as it was demonstrated by Zhang *et al.*[8] using Degarelix API. The treatment of the peptide with standard Fmoc-deprotecting bases, such as 1,8-diazabicyclo[5.4.0]-undec-7-ene (DBU) or piperidine with the traces of water, resulted in the formation of up to 7% of hydantoin impurity. Thus, the use of high-quality anhydrous reagents is mandatory for the Degarelix preparation. As reported by the same authors, piperidine shows a lower ability to induce the Hor-Hyd rearrangement than DBU. Unfortunately, epimerization is not completely avoided even with this base. Furthermore, piperidine is currently reported as a controlled substance in Table II of the United Nations Convention Against Illicit Traffic in Narcotic Drugs and Psychotropic Substances.[9] This aspect noticeably complicates the application of piperidine for the industrial manufacturing of not only Degarelix, but also the other peptides, because of the rigid requirements applied for the purchase, storage and disposal of this reagent.

To overcome all these problems, novel approaches are requested for the manufacturing of Degarelix. In the course of our investigation on Degarelix synthetic route, we previously proposed a novel method, where side-chain modification of the peptide is carried out on solid phase from corresponding *p*-nitro derivatives, avoiding by that the contact of Hor with the

bases.[10] In this study we describe an alternative approach, where Fmoc-deprotection is carried out by means of the bases, which can minimize the Hor-Hyd rearrangement.

RESULTS AND DISCUSSION

The Fmoc group, commonly used in SPPS, is cleaved under mild basic conditions by β-elimination.[11,12] The organic base of choice in Fmoc SPPS is a piperidine solution in dimethylformamide (DMF), or, alternatively, in "green" solvents.[13] Along with fast Fmoc deprotection, piperidine also functions as a scavenger for the formation of the side product dibenzofulvene, which is a highly reactive electrophile and can reattach to the liberated amine function (Figure 2).

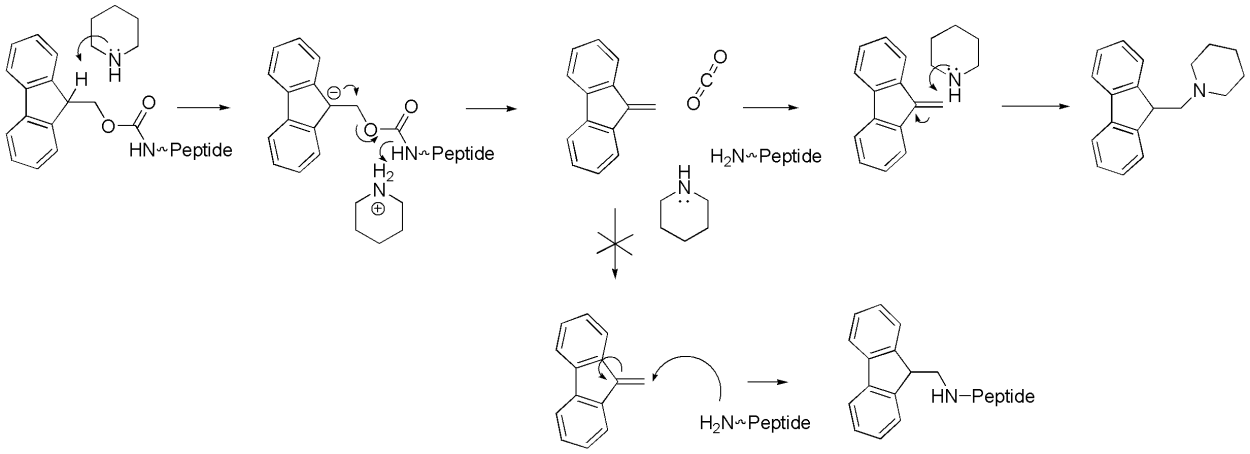
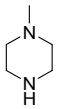


Figure 2. Scheme of Fmoc deprotection by piperidine.

However, several drawbacks of piperidine used for the industrial production of peptides, as well as its possible induction of side reactions, triggered the search for suitable alternatives. In the case of Degarelix, the possibility of the Hor-Hyd rearrangement in the presence of bases significantly limits the choice of the deprotection mixture and, therefore, the applicability of Fmoc-based protections in the synthesis. In previous works, it was found that piperidine can be often substituted by other amines, e.g piperazine, morpholine, diethylamine.[14,15] In order to select appropriately the organic base, which can be used for the Fmoc-deprotection and, at the same

time, does not induce Hor-Hyd rearrangement, we carried out a detailed screening of amines with different pK_a values (Table 1, Figure S1).

Table 1. Trend of [Aph(Hyd)]^5-Degarelix formation in the presence of different bases

Base	Chemical structure	pK_a	Base in DMF, %	Monitoring time	Hydantoin, % (±0.05)	Hydantoin in the presence of 5% water, % (±0.05)
DBU		13.50	2	20 min	< 0.15	< 0.15
				1 h 40 min	0.69	1.38
				20 h	4.97	10.14
Pyrrolidine		11.27	20	20 min	< 0.15	< 0.15
				1 h 40 min	< 0.15	< 0.15
				20 h	< 0.15	< 0.15
Piperidine		11.22	20	20 min	< 0.15	0.22
				1 h 40 min	0.16	0.26
				20 h	0.18	0.67
tert-Butylamine		10.68	30	20 min	< 0.15	< 0.15
				1 h 40 min	< 0.15	< 0.15
				20 h	< 0.15	0.43
N-Methyl piperazine		9.14	5	20 min	< 0.15	< 0.15
				1 h 40 min	< 0.15	< 0.15
				20 h	< 0.15	< 0.15
Morpholine		8.36	50	20 min	< 0.15	< 0.15
				1 h 40 min	< 0.15	< 0.15
				20 h	< 0.15	< 0.15

The stability of Degarelix was tested in the presence of these amines as a function of time, ranging from 20 min (a standard, single Fmoc deprotection cycle) to 1 h 40 min (5 deprotection cycles to incorporate 4 amino acids after Aph(Hor) and to acetylate the peptide) and finally to 20 h. As expected, the treatment of Degarelix with half of the amines induced time-dependent

hydantoin formation. In most of the cases, the addition of 5% water to the mixture resulted in an increased amount of the hydantoin impurity formed. The strongest base of the series, DBU, favored this rearrangement even in the absence of water, as it was shown by Zhang *et al.*[8] Despite the low amount of hydantoin in the case of pyrrolidine, the degradation of the peptide, with appearance of other impurities, was observed. In particular, MS study showed the formation of an adduct of Degarelix with pyrrolidine, which may open the dihydroorotic cycle. Therefore, these bases were both excluded in the further investigations. In the six-membered ring amine series the influence of the pK_a of the base on the Hor moiety rearrangement was almost negligible (the amount of hydantoin ranged from 0.10% to 0.16%). Interestingly, no hydantoin impurity was found in the case of *tert*-butylamine, probably due to its sterical hindrance and prevention of the deprotonation of the Hor moiety in the first step of the process of isomerization.

The kinetics of Fmoc deprotection in the presence of the amines (with the exceptions of DBU and pyrrolidine) was studied using the Rink amide resin and model amino acids (Fmoc-Phe(*p*-NO_2)-OH and Fmoc-Ser(*t*Bu)-OH) attached to the solid support (Figure 3, S2, S3).

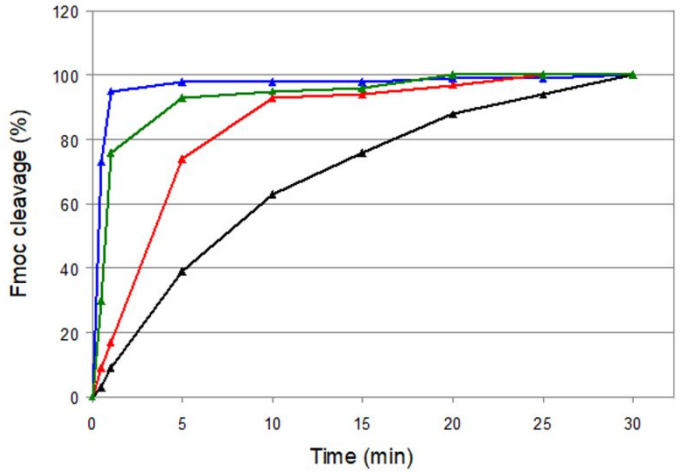


Figure 3. Fmoc cleavage from Fmoc-Phe(*p*-NO_2)-Rink amide resin (blue – piperidine, green – *tert*-butylamine, red – morpholine, black – N-methylpiperazine).

As it was expected, the rate of Fmoc cleavage depended on the pK_a values of the bases. The strongest bases piperidine and *tert*-butylamine induced almost complete Fmoc cleavage in a few minutes. The same trend was observed for the Fmoc-protected Rink amide resin and *tert*-butyl ether side-chain protected serine. On the contrary, the weaker bases morpholine and N-methylpiperazine performed the Fmoc removal at a slower rate. Hence, although they do not induce the Hor-Hyd rearrangement, they may favor the formation of amino acid deletion products during the SPPS process of Degarelix.

Among the bases tested, *tert*-butylamine both afforded rapid cleavage of the Fmoc protecting group and induced negligible Hor-Hyd rearrangement over a prolonged time period. For this reason, *tert*-butylamine was used in the Fmoc deprotection step of the full SPPS of Degarelix. The effect of *tert*-butylamine was investigated in the SPPS using both the preformed Fmoc-Aph(Hor)-OH amino acid and *p*-nitro precursor, accordingly to the strategy previously reported.[10] The results were compared with the full SPPS process using piperidine as a base for the Fmoc deprotection, focusing the attention on the Hor-Hyd rearrangement (Table 2, Fig. S4-6).

Table 2: Results of SPPS experiments of Degarelix using *tert*-butylamine or piperidine as base for the Fmoc deprotection step.

Entry	Strategy of SPPS Degarelix preparation	Base used for Fmoc deprotection	HPLC purity (crude product), % (±0.05)	[Aph(Hyd)]^5-Degarelix, % (±0.05)
1	Full SPPS	*tert*-butylamine	87.50	< 0.15
2	Full SPPS[8]	piperidine	83.99	0.37
3	5-Phe(*p*-NO_2)-Degarelix reduction and Hor coupling	*tert*-butylamine	88.63	< 0.15
4	5-Phe(*p*-NO_2)-Degarelix reduction and Hor coupling[10]	piperidine	87.04	< 0.15

In both cases where *tert*-butylamine was used as a base (Table 2, Entry 1 and 3), the crude peptide obtained showed high purity and yield without detectable [Aph(Hyd)]^5-Degarelix impurity. This aspect is particularly remarkable for the full SPPS approach (Entry 1), where the Hor function was inserted during the building up of the peptide sequence and not at the end. Furthermore, in contrast with piperidine, *tert*-butylamine has no concern from regulatory and safety point of view, thus it poses no restriction for the storage or use in the Pharmaceutical industry. For these reasons, *tert*-butylamine can be considered an excellent substitute to piperidine for Fmoc deprotection in the solid-phase synthesis of the peptide. Both *p*-nitro perecursor reduction approach described in Part 1 of this study and the method, where *tert*-butylamine is used, give excellent results in terms of purity and yield, when compared with the conventional stepwise synthesis. Though they give similar results, the latter approach seems to be more convenient from the industrial point of view, since less unit operations are required to prepare the active pharmaceutical ingredient.

In conclusion, here we evaluated a series of the organic bases able to remove Fmoc protective group in order to substitute piperidine for the preparation of gonadotropin-releasing hormone antagonist Degarelix by solid-phase synthesis. Almost all the bases of this series induced either the rearrangement of the dihydroorotic moiety to hydantoin or the formation of other impurities. The only base able to both ensure a fast Fmoc cleavage and negligible Hor-Hyd isomerisation was *tert*-butylamine. Thus, this base can be considered a suitable alternative to piperidine for SPPS manufacturing of Degarelix or other Hor-containing peptides using Aph(Hor) (both ready-to-use or assembled on resin) during the elongation of the amino acid sequence.

EXPERIMENTAL PART

Materials and Methods

Iris Biotech: N,N-dimethylformamide (DMF), dichloromethane (DCM), N,N-diisopropylethylamine (DIPEA), trifluoroacetic acid (TFA), piperidine, Fmoc-protected Rink amide resin; *Sigma Aldrich:* acetonitrile for mass spectrometry (MS) (>99,9%), TFA for MS (>99,9%), methyl *tert*-butyl ether (MTBE), triisopropylsilane (TIS), acetic anhydride, *Carbosynth*: Ethyl (hydroxyimino)cyanoacetate (Oxyme Pure), N,N′-diisopropylcarbodiimide (DIC); *GL Biochem:* Fmoc-Nal-OH, Fmoc-Cpa-OH, Fmoc-Pal-OH, Fmoc-Ser(*t*Bu)-OH, Fmoc-D-Aph(Cbm)-OH, Fmoc-Aph(Hor)-OH, Fmoc-Leu-OH, Fmoc-Lys(Boc, *i*Pr)-OH, Fmoc-Pro-OH, Fmoc-D-Ala-OH.

Merck: DBU, pyrrolidine, *tert*-butylamine, N-methyl piperazine, morfoline.

UPLC chromatography: UPLC analyses were performed on Agilent Technologies 1290 Infinity (stability experiments) and Agilent Technologies 1290 Infinity II instruments using Acquity UPLC BEH C18 1.7µm 3×150 mm column. Analytical method 1: eluent A, TFA/H_2O 0.1% *v/v*; eluent B: TFA/acetonitrile 0.1% *v/v*; detection at 224 nm; gradient mode: 0 min – 25% of eluent B, 30 min – 45% of eluent B. Analytical method 2: eluent A, TFA/H_2O 0.1% *v/v*; eluent B: TFA/acetonitrile 0.1% *v/v*; detection at 224 nm; gradient mode: 0 min – 25% of eluent B, 38 min – 45% of eluent B, 47 min – 60% of eluent B.

Mass spectrometry analysis: mass spectra were acquired in the LC-MS mode on a Agilent 6530 mass accuracy Q-ToF, operating in the positive mode.

Study of the stability of Degarelix in presence of the bases

A sample of Degarelix API (130 mg/ml) was dissolved in the solution of the base in DMF. The aliquots were taken at different times and analysed by UPLC.

Study of the kinetics of Fmoc deprotection

10 mg of Fmoc-protected Rink amide resin were swelled in DMF for 15 min and the selected amine was added to the suspension to obtain the required concentration and 1 ml of the total volume of the deprotection mixture. The reaction mixture was stirred and samples of the solution (10 μL) were taken after the desired time intervals. The samples were diluted by 990 μL of DMF in an 1 cm quartz cuvette. The absorbance was measured at 301 nm and the loading was calculated by the formula $L = (A_{301} \times V \times d)/(K \times w \times M)$, where L - resin loading, A_{301} - absorbance at 301 nm, V - volume of the cleavage solution, K - extinction coefficient (7800 mL/mmol×cm), w - optical path length, M - weight (g) of the resin sample. In the same way the experiments with Fmoc-Ser(*t*Bu)-Rink Amide Resin and Fmoc-Phe(*p*-NO_2)-Rink amide resin were carried out.

Peptide synthesis

Synthesis of Degarelix with tert-butylamine and piperidine. The synthesis was carried out using CS-Bio 936 system and 250 g of Rink amide resin (loading 0.65 mmol/g). The resin was swollen in 1.5 L of DMF for 30 min, Fmoc deprotected with 30% *tert*-butylamine in DMF (three cycles for 5, 5 and 10 min) (in the case of piperidine all Fmoc deprotections were carried out with 20% piperidine in DMF, two cycles for 5 and 15 min) and washed 4 times with 1.5 L of DMF. The solid-phase synthesis was carried out using 3 eq of protected amino acids that were preactivated during 3 min with 3 eq of Oxyma Pure and 3 eq of DIC, and subsequentry coupled in 1 h. The unreacted amino groups were capped with 10% solution of acetic anhydride in DMF in 20 min up to D-Aph(Cbm) and at the end of the synthesis N-terminal amino group was acetylated using 3 eq of acetic acid preactivated with 3 eq of Oxyma Pure and 3 eq of DIC during 3 min. The final acetylation was repeated twice. Peptide-resin was washed with DMF (2×1.5 L) and DCM (2×2 L) and the peptide was cleaved from the resin with 5 L of the mixture TFA/TIS/water (95:2.5:2.5 *v/v*) and precipitated in 10 L of MTBE. The product was filtered off and dried.

The identity of the peptide was confirmed by ESI MS:

Degarelix: $[M+H]^+_{calc} = 1631.75$, $[M+H]^+_{exp} = 1631.72$

Yield (*t*-Butylamine): 178 g (67%).

Yield (Piperidine): 172 g (65%).

Synthesis of Degarelix with tert-butylamine and 5-Phe(p-NO_2)-Degarelix reduction.

The synthesis was carried out as described previously with 500 g of of Rink amide resin (loading 0.65 mmol/g).[10] Instead of piperidine for the Fmoc deprotection 30% *tert*-butylamine in DMF was used (three cycles for 5, 5 and 10 min).

Yield: 333 g (63%).

ASSOCIATED CONTENT

Supporting information

UPLC profiles of Degarelix in presence of various bases; kinetics of Fmoc deprotection from Fmoc-Rink Amide Resin and Fmoc-Ser(*t*Bu)-Rink Amide Resin using various bases; UPLC profiles of Degarelix prepared step-by-step approach using TBA and piperidine for Fmoc deprotection as well as UPLC profile of Degarelix prepared with TBA from 5-Phe(*p*-NO_2) precursor

AUTHOR INFORMATION

Corresponding Authors

E-mail: ivan.guryanov1@gmail.com (I.G.).

E-mail: antonio.ricci@fresenius-kabi.com (A.R.).

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Steinberg, M. Degarelix: a Gonadotropin-Releasing Hormone Antagonist for the Management of Prostate Cancer. *Clin. Therapeutics* **2009**, *31*, 2312-2331.

(2) Doehn, C.; Sommerauer, M.; Jocham, D. Degarelix and its Therapeutic Potential in the Treatment of Prostate Cancer. *Clin. Interv. Aging* **2009**, *4*, 215-223.

(3) Clinton, T. N.; Woldu, S. L.; Raj, G. V. Degarelix Versus Luteinizing Hormone-Releasing Hormone Agonists for the Treatment of Prostate Cancer. *Expert Opin. Pharmacother.* **2017**, *18*, 825-832.

(4) Nestor, J. J. The Medicinal Chemistry of Peptides. *Curr. Med. Chem.* **2009**, *16,* 4399-4418.

(5) Zhou, N.; Gao, X.; Lv, Y.; Cheng, J.; Zhou W.; Liu, K. Self-Assembled Nanostructures of Long-Acting GnRH Analogs Modified at Position 7. *J. Pept. Sci.* **2014**, *20*, 868-875.

(6) Kaneti, J.; Kirby, A. J.; Koedjikov A. H.; Pojarlieff, I. G. Thorpe–Ingold effects in Cyclizations to Five-Membered and Six-Membered Rings Containing Planar Segments. The Rearrangement of N(1)-Alkyl-Substituted Dihydroorotic Acids to Hydantoinacetic Acids in Base. *Org. Biomol. Chem.* **2004**, *2*, 1098-1103.

(7) Koedjikov, A. H.; Blagoeva, I. B.; Pojarlieff I. G.; Stankevic, E. β-Ureido Acids and Dihydrouracils. Part 15. Effect of Allylic Strain on Ring Opening of 1,6-Disubstituted Dihydrouracils. *J. Chem. Soc., Perkin Trans. II* **1984**, 1077-1081.

(8) Zhang, H.; Fomsgaarg, J.; Staerkaer, G. Method for the Manufacture of Degarelix. WO2010121835 A1, October 28, **2010.**

(9) https://www.incb.org/incb/en/precursors/technical_reports/2018.html.

(10) (a) Guryanov, I.; Orlandin, A.; Biondi, B.; Formaggio, F.; Visentini, D. Process for the Manufacture of Degarelix and its Intermediates. WO2017103275 A1, June 22, 2017. (b) Guryanov, I.; Orlandin, A.; Viola, A.; Biondi, B.; Badocco, D.; Formaggio, F.; Ricci, A.; Cabri, W. Overcoming Chemical Challenges in the Solid-Phase Synthesis of High-Purity GnRH

Antagonist Degarelix. Part 1. *Org. Process Res. Dev.* **2019**, XXXX, XXX, XXX-XXX. DOI: 10.1021/acs.oprd.9b00430.

(11) Fields, G. B. in *Methods in Molecular Biology*, *Peptide Synthesis Protocols*; Pennington, M. W., Dunn, B. M., Eds.; Humana Press: Totowa, NJ, **1994**; Vol. 35, pp. 17-27.

(12) Stigers, K. D.; Koutroulis, M. R.; Chung, D. M.; Nowick, J. S. Fmoc*: a More Soluble Analogue of the 9-Fluorenylmethoxycarbonyl Protecting Group. *J. Org. Chem.* **2000**, *65,* 3858-3860.

(13) Kumar, A.; Niyi, A.; Nandhini, K. P.; Collins, J. M.; Albericio, F.; de la Torre, B. G. Troubleshooting When Using γ-Valerolactone (GVL) in Green Solid-Phase Peptide Synthesis. *Org. Process Res. Dev.* **2019**, *235*, 1096-1100.

(14) Wuts, P. G. M.; Greene, T. W. *Greene's Protective Groups in Organic Synthesis,* 4th edit.; Wiley: Hoboken, NJ, **2007**; pp. 712-713.

(15) Ralhan, K.; Kumar, V. G. K.; Gupta, S. Piperazine and DBU: a Safer Alternative for Rapid and Efficient Fmoc Deprotection in Solid Phase Peptide Synthesis. *RSC Adv.* **2015**, *5*, 104417.

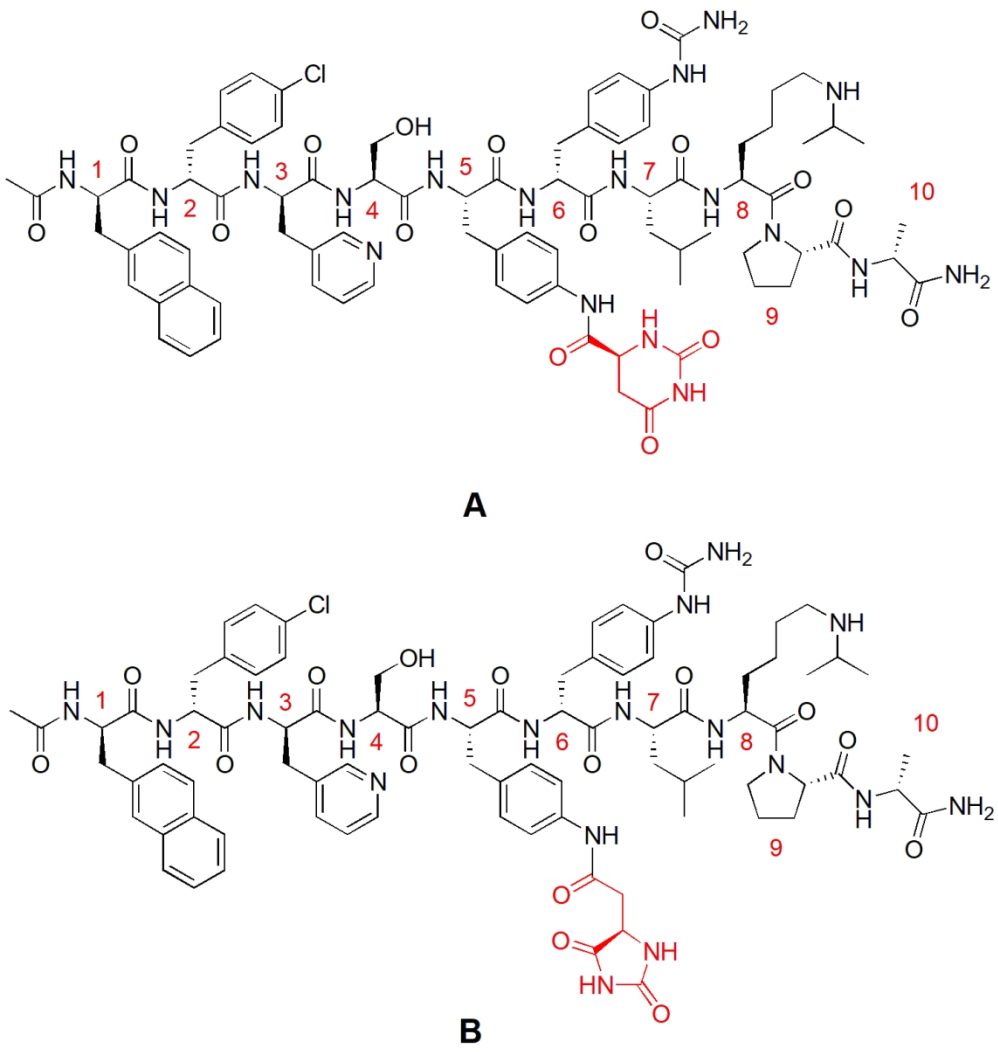


Figure 1. Chemical structures of Degarelix (A) and hydantoin isomer (B) (Hor moiety and the corresponding hydantoin are evidenced in red).

526x552mm (72 x 72 DPI)

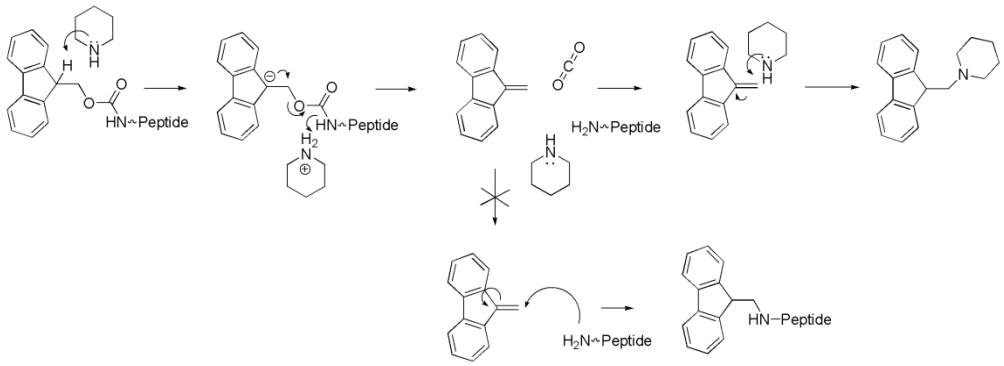


Figure 2. Scheme of Fmoc deprotection by piperidine.

208x75mm (300 x 300 DPI)

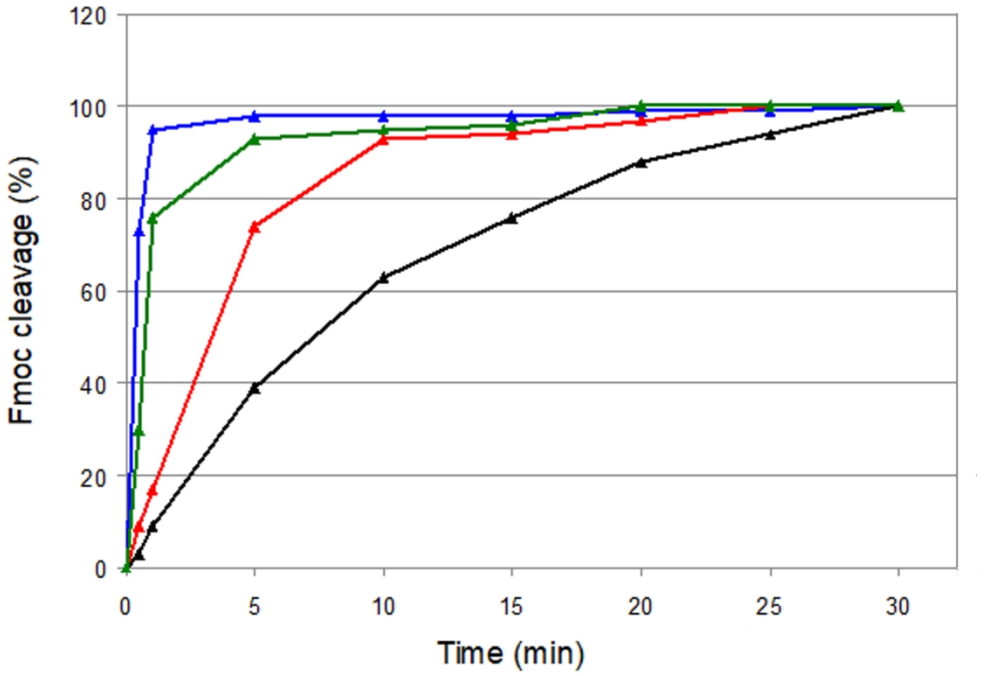


Figure 3. Fmoc cleavage from Fmoc-Phe(*p*-NO_2)-Rink amide resin (blue – piperidine, green – *tert*-butylamine, red – morpholine, black – N-methylpiperazine).

604x439mm (72 x 72 DPI)