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1 **Forced degradation study of quinapril by UPLC-DAD and UPLC/MS/MS: Identification of by-products**
2 **and development of degradation kinetics**

3 **Abstract**

4 Quinapril undergoes a significant degradation in the solid state, especially in the presence of humidity,
5 temperature and pharmaceutical excipients. Since dissolution increases the degradation, hydrolytic reactions are
6 among the most common processes involved in drug degradation. Improving the knowledge regarding drug
7 stability, especially concerning the critical factors that can influence the stability of the active substance in
8 solutions, such as the temperature, the pH and the concentration of catalytic species usually acids or bases is
9 essential for pharmaceutical use; the aim of this study was therefore to develop a new chromatographic method
10 for rapidly and accurately assess the chemical stability of pharmaceutical dosage in acidic, neutral and alkaline
11 media at 80°C according to the ICH guidelines. Ultra High Performance Liquid Chromatography (UPLC)
12 coupled to electrospray ionization tandem mass spectrometry was used for the rapid and simultaneous analysis of
13 quinapril and its by-products. Separation was achieved using a BEH C18 column and a mixture of acetonitrile -
14 ammonium hydrogencarbonate buffer (pH 8.2; 10 mM) (65:35, v/v) with a flow rate of 0.4 mL/min as a mobile
15 phase. This method allowed the drug by-products profiling, identification, structure elucidation and quantitative
16 determination of by-products under stress conditions. The developed method also provides the determination of
17 the kinetic rate constants for the degradation of quinapril and the formation of its major by-products. Kinetic
18 study and the structure elucidation of by-products allow the development of a complete model including
19 degradation pathway observed under all tested conditions.

20 **Keywords:** Quinapril, Stress testing, ICH guideline (Q1A R2), UPLC-MS/MS, Degradation products,
21 Degradation pathway.

22 **Introduction**

23 Quinapril (3S)-2-[(2S)-2-[[[(1S)-1-(Ethoxycarbonyl)-3-phenylpropyl]amino]-1-oxopropyl]-1,2,3,4-tetrahydro-3-
24 isoquinolinecarboxylic acid hydrochloride [1-2] is a nonpeptide, nonsulfhydryl angiotensin converting enzyme
25 inhibitor (ACEI) belonging to the third class of ACEI [2-4]. It is used for the treatment of cardiovascular
26 diseases such as hypertension and congestive heart failure, either alone or in conjunction with other drugs [5-6].
27 Quinapril is an oral prodrug, yielding via metabolism a free active diacid compound, quinaprilat [4-7], which
28 acts as an ACEI [8][9].

29 Previous studies showed that, like many dipeptide ACEI such as lisinopril [10], moexipril [11-13], enalapril

30 maleate [14], benazepril [15] and ramipril [16], quinapril hydrochloride is unstable in solid phase (in
31 pharmaceutical dosage), especially in the presence of humidity, temperature, and pharmaceutical excipients [17-
32 18]. The influence of these factors on the stability of quinapril and the pathway characterizing its degradation in
33 the solid phase were investigated by Beata Staniz [17-18]. Analysis of the degradation of quinapril in the solid-
34 state showed that Quinaprilat (hydrolysis product), the diketopiperazine ester (cyclization product) and the
35 diketopiperazine acid (cyclization and hydrolysis product) were the main products [17-18].

36 Although a significant degradation occurs in the solid state, particularly in amorphous systems, the rate of drug
37 degradation is faster in solution [19].

38 Hydrolytic reactions are among the most common processes for drug degradation. Improving the knowledge
39 regarding the critical factors that can influence the stability of the active substance in solution, such as
40 temperature, pH and concentration of catalytic species usually acids or bases [20] are of major importance in
41 pharmaceutical development, which include degradation studies in acidic, neutral and alkaline media. In fact,
42 drug impurity profiling, identification, structure elucidation and quantitative determination of impurities and
43 degradation products in bulk drug materials and pharmaceutical formulations is one of the most important fields
44 of activities in modern pharmaceutical analysis. The reason for the increasing importance of this area is that
45 unidentified, potentially toxic impurities are health hazards. Therefore, in order to increase the safety of drug
46 therapy, impurities should be identified and determined by selective methods [20-22].

47 In the literature, there is no reported work on the chemical stability of quinapril under stress conditions. Further
48 studies are therefore needed to characterize the by-products formed by quinapril degradation under acidic,
49 neutral and alkaline media. According to the international conference on harmonization (ICH), accelerated
50 stability studies have to be carried out, according to the stability test guideline Q1A (R2) [23] to establish its
51 inherent stability characteristics, leading to the development of a separation method for the degradation products
52 and hence to support the stability-indicating nature of the method.

53 Many analytical methods have been reported in the literature for the analysis of quinapril such as gas
54 chromatography with negative-ion chemical ionization mass spectrometry (MS) or electron-capture detection
55 [24], capillary electrophoresis [25], high performance liquid chromatography with fluorescence [24], UV [2] or
56 radiochemical detection [26] as well as electrospray ionization (HPLC/ESI) [2], and MALDI-TOF MS[27]. The
57 considered techniques include also UV spectroscopy [28], square wave voltammetry [29], ultraperformance
58 liquid chromatography tandem mass spectrometry (UPLC-MS/MS) [28], ultra-thin-layer chromatography mass
59 spectrometry and thin-layer chromatography mass spectrometry [30]. However, to our knowledge, on the one

60 hand no study demonstrates the ability of ultra-performance liquid chromatography (UPLC) to resolve the
61 separation of quinapril and its degradation products, and on the other hand the identification of the by-products
62 has not been previously investigated. In order to better understand the mechanism of quinapril degradation, a
63 chromatographic method involving diode array detector (DAD) and tandem mass spectrometry (MS-MS) has
64 been therefore developed in this study. Degradation of quinapril according to the ICH guidelines has been
65 performed and a complete mechanism for the quinapril degradation under basic, neutral and acidic conditions
66 has been proposed. Since no data on kinetics of quinapril degradation could be found in the published literature,
67 the purpose of this paper was also to present kinetic studies of disappearance and appearance of quinapril and
68 major degradation products, respectively.

69 **2. Experimental conditions**

70 **2.1. Chemical standards and solutions**

71 Quinapril was provided by the National laboratory of control of drugs and screening dopage (Tunisia). All
72 mobile phase were prepared from reagent-grade chemicals and purified water (UPW) delivered by a Millipore
73 system (MilliQ Elga, France). Acetonitrile (ACN) for UPLC-DAD and UPLC-MS/MS was purchased from
74 Fisher Chemicals (HPLC grade, Loughborough, Leicestershire, UK) and JT Baker (LC-MS grade, United
75 States), respectively. Aqueous solution of ammonium hydrogenocarbonate (Prolabo, Paris, France), (10 mM)
76 was adjusted at $\text{pH} = 8 \pm 0.1$ with a 911 pH meter (Knick, Germany).

77 The mobile phases were filtered through a 0.2 μm cellulose acetate membrane filter (Sartorius stedim biotech,
78 Goettingen, Germany) before filling the eluent organizer.

79 **2.2. Ultra Performance Liquid Chromatography – Diode Array Detector (UPLC-DAD)**

80 Ultra performance liquid chromatography (UPLC) was performed using a Waters Acquity H-class system
81 (Waters Corporation, Milford, MA). Samples and standards were maintained at 4°C in the sampler manager
82 prior to analyses. 5 μL of samples were then injected into an Acquity BEH C18 column (100 x 2.1 mm, 1.7 μm ,
83 Waters) thermostated at 45°C. Different compositions of mobile phases were evaluated to achieve the separation
84 of quinapril and its degradation products. The general composition of the eluent consisted of an UPW/ACN
85 mixture. Effects of the ratio UPW/ACN, pH and addition of buffering species (ammonium hydrogencarbonate,
86 formic acid) on the chromatographic separation were evaluated. Flow rate was set at 0.4 mL min^{-1} and detection
87 was made between 190 and 500 nm. Waters EmpowerTM chromatography software was used to control the
88 chromatographic system and to record data.

89 **2.3. Ultra Performance Liquid Chromatography – Tandem Mass Spectrometry (ULPC-MS/MS)**

90 Liquid Chromatography Tandem mass spectrometry system consisted of an Acquity UPLC system (Waters
91 Corporation, Milford, MA) coupled with a triple quadrupole detector (Quattro premier, Micromass). 5 μ L of
92 samples from the hydrolytic degradation experiments were separated on an Acquity BEH C18 column (100 x 2.1
93 mm, 1.7 μ m, Waters). Isocratic separation was carried out with a mixture of eluent A (65%, vol.): eluent B (35%
94 vol.) at a flow rate of 0.4 mL min⁻¹. Eluent A consisted of an aqueous solution of ammonium hydrogencarbonate
95 (10 mM, pH 8.1); eluent B was ACN. Sampler manager and column oven were kept at 4°C and 45°C,
96 respectively. The MS analysis was performed by means of an electrospray ionization (ESI) interface both in
97 positive or negative ion mode with a capillary voltage of \pm 3 kV. Indeed, according to the quinapril structure
98 both positive and negative modes could be applied, owing to the carboxylic and amide functional groups of
99 quinapril which could give protons during the ionization process on the one hand, and since both molecules
100 could be protonated on the other hand. In accordance with preliminary investigation as well as with literature
101 data [1-2, 31], a positive mode was chosen. Product ion spectra of quinapril and its degradation products were
102 acquired using N₂ as nebulizer and drying gas. The cone gas flow and the desolvation gas flow were set to 50 L
103 h⁻¹ and 750 L h⁻¹, respectively. The source temperature and the desolvation gas temperature were 120 °C and 350
104 °C, respectively. The mass range (m/z) was 50-600.

105 **2.4. Stress study**

106 Stress studies were carried out under the conditions of heat and hydrolysis as mentioned in ICH Q1A (R2)
107 guideline [23]. Hydrolytic decomposition of quinapril was performed at 80 °C with 0.1 N HCl, water and 0.1 N
108 NaOH at an initial drug concentration of 0.5 mg mL⁻¹ and 0.1 mg mL⁻¹. However, because quinapril was found
109 to be highly affected to alkaline degradation, studies were performed by reducing the concentration of sodium
110 hydroxide to 0.01 N. The approach suggested by Bakshi and Singh [32] was adopted for this study. A minimum
111 of four samples were generated for each stress condition; the blank solution stored under normal conditions, the
112 blank subjected to the same stress as the drug (quinapril), zero time sample containing the drug (which was
113 stored under normal conditions), and the drug solution subjected to stress treatment.

114 **2.5. Separation study and development of stability-indicating method**

115 UPLC-DAD experiments were performed on all reaction solutions individually, and then on a mixture of
116 degraded drug solutions. In order to obtain acceptable separation between quinapril and its degradation products,
117 as well as between the different degradation products, different logical modifications like change in pH, mobile
118 phase composition and column temperature adjustment were tested. To allow the transposition of the

119 chromatographic method from UPLC-DAD to UPLC-MS/MS simple rules should be respected; eluent
120 composition must only involve volatile compounds to avoid salt deposit into the cone. In the first step, a mixture
121 of UPW acidified at pH = 3 by formic acid and ACN was used as a mobile phase. Formic acid was selected
122 because the apparent pKa of quinapril is equal to 5.7 and the conventional degradation pathway of ACEI leads to
123 the formation of carboxylic acid by the ester function cleavage. However non-reproducible retention time and
124 signals intensity were obtained with formic acid. Elution with ammonium hydrogencarbonate as the buffering
125 compound led to more relevant results for the separation of quinapril from its degradation products; it also
126 resulted in a retention time observed on the UPLC-DAD system comparable to that obtained in the UPLC-
127 MS/MS system. The selected composition of the mobile phase consisted therefore of a mixture of 65 % (vol.)
128 ammonium hydrogencarbonate 10 mM in UPW and 35 % (vol.) of ACN with a flow rate of 0.4 mL min⁻¹. From
129 a practical standpoint, ammonium hydrogencarbonate is an ideal buffer for chromatographers since it provides
130 excellent chromatographic behaviour and reproducible separation. Satisfactory results were obtained by the
131 standard diode array and MS detection by using this buffer at a concentration of 10 mM. A major reason for
132 using this concentration was to achieve maximum sensitivity of UV detection at low wavelengths. The detector
133 was operated at 211 nm since this ACEI weakly absorbs in the UV region. This method was shown to provide
134 fast and efficient separation of quinapril from its degradation products. In addition, hydrogencarbonate buffer is
135 thermally decomposed in CO₂ and NH₃ in the MS interface since 60°C [33].

136 **3. Results and discussion**

137 **3.1. Degradation behaviour of quinapril under thermal hydrolysis (alkaline, neutral and acidic conditions)**

138 The estimation of the impurity profiles of bulk drug substances is one of the most important fields of activity in
139 contemporary industrial pharmaceutical analysis. In general impurities present in excess of 0.1% should be
140 identified and quantified by sufficiently selective methods, but drug registration authorities are increasingly
141 interested by impurities in the range 0.01-0.1% for many reasons [21]. The guidance also indicates that
142 degradation products that are not formed under accelerated or long term conditions do not need to be evaluated.
143 Therefore, data from this study are typically used to evaluate quinapril stability. As shown in figure.1, all
144 quinapril by-products detected under accelerated stability testing exceeded the identification thresholds in all
145 stress conditions.

146 Quinapril stability under various conditions (alkaline, neutral and acidic) at 80°C was assessed as mentioned
147 above and the results of the stability studies are collected in figure.1. All experiments were conducted at two
148 concentration levels of quinapril (0.114 mM in alkaline medium and 1.14 mM in neutral and acidic media). The

149 results indicated that quinapril is degraded under the various considered conditions. Chromatographic analysis
150 showed that quinapril degradation occurred faster in alkaline medium compared to both acidic and neutral
151 media. Under alkaline conditions, quinapril degradation was observed from the first minutes yielding the
152 formation of two by-products eluted at a retention time of 0.55 and 0.66 min respectively. The chromatogram,
153 obtained on a C18 column (Figure 1.a), shows a very broad peak relative to the quinapril (RT= 1.35 min, ω =
154 0.48 min) and a peak splitting relative to the by-product eluted at 0.66 min. This chromatographic phenomenon
155 may be attributed to an equilibrium between the cis- and the trans-conformers that arose from the hindered
156 rotation around the amide bond having partial double bond character. It is consistent with studies showing that
157 similar chromatographic phenomenon has been observed with other ACEI such as enalapril [34], enalaprilat [35]
158 and lisinopril [36]. However, additional experiments by LC-DAD, which could be later considered, are needed to
159 confirm this assumption.

160 Acidic and neutral hydrolysis at 80°C led to the formation, within the first minutes, of a major by-product eluted
161 at 8.92 min. Other degradation products were also observed but after a significant contact time. The full scan
162 spectra were recorded for solutions obtained after 22 h of contact with 0.1 M HCl and water. As shown in fig. 1
163 the chromatographic method was able to resolve all the components in a mixture of stressed sample. The peaks
164 associated to degradation products were not only well-resolved from the drug, but also from one another. The
165 method thus proved to be selective and stability-indicating either for the study of acidic, neutral and alkaline
166 hydrolysis. On the other hand, reversed-phase UPLC conditions provided a general measure of the polarity of
167 each compound, useful for the interpretation of substructural differences between related compounds.

168 Comparison of chromatograms obtained under acidic and neutral conditions shows that quinapril present the
169 same UPLC profile in the two media (same retention time and same UV spectra). Nevertheless, the rate of
170 degradation under acidic hydrolysis is faster than under neutral hydrolysis. After a contact time of 23 hours
171 approximately 89 % of the initial amount of quinapril has been degraded under neutral conditions leading to the
172 formation of 5 separated by-products (Fig. 1.c). The UPLC profile obtained for the neutral degradation of
173 quinapril revealed that among these products, four are eluted within only one minute retention time, namely
174 before the starting material, indicating that these products are more polar than quinapril. These products
175 corresponded to 6% of the amount of degraded quinapril after 24 h contact time, whereas the major by-product
176 eluted at 8.92 min corresponded to 81% of that amount.

177 Under acidic conditions, 99 % of the drug was degraded after 24 h contact time at 80°C. Similarly to the neutral
178 conditions, the by-product eluted at 8.92 min was the major product with an amount of 70% of the degraded
179 quinapril, whereas the other by-products corresponded to only 9 % of the degraded drug.

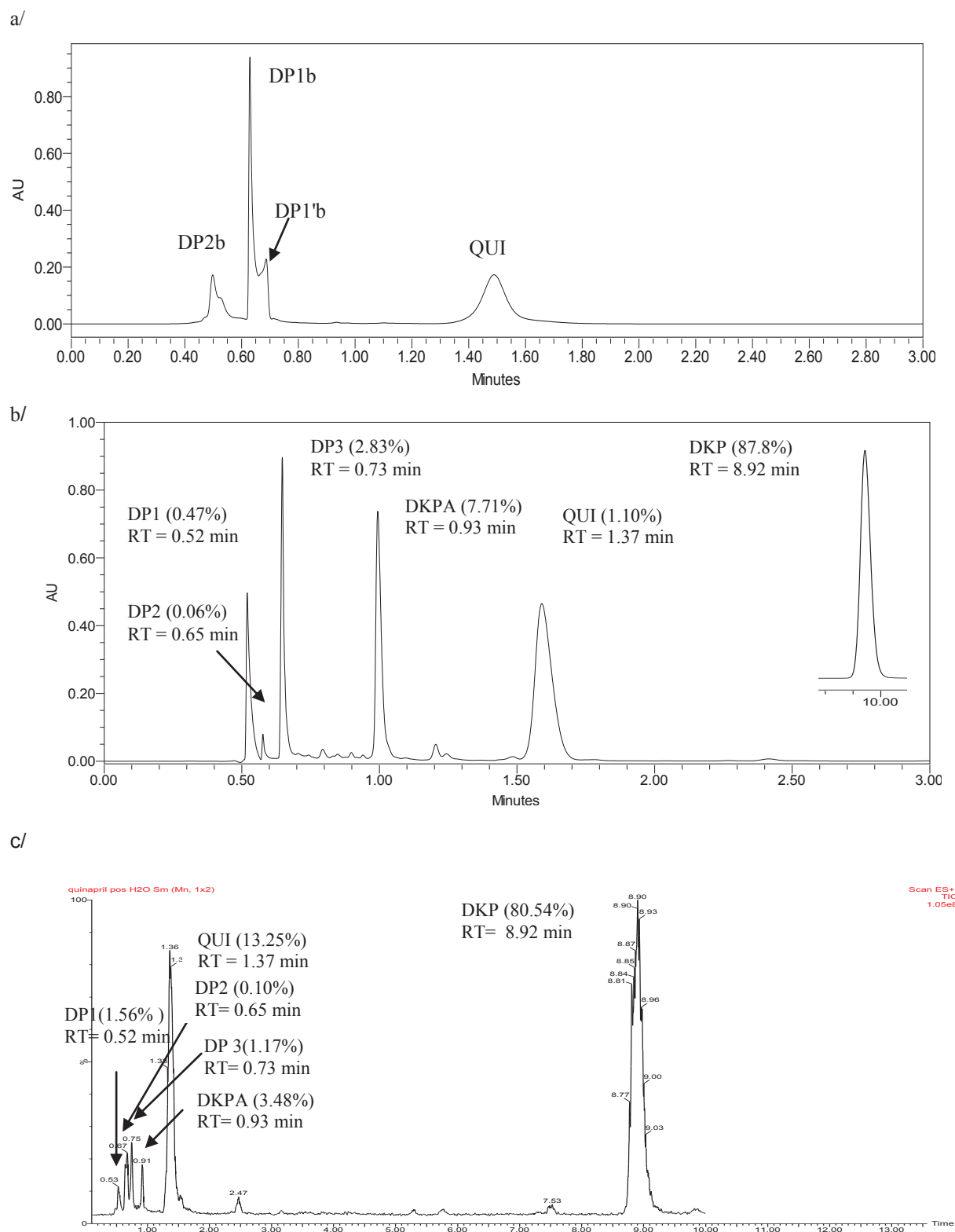


Fig. 1. Chromatograms of quinapril and its degradation products obtained under alkaline (a), acid (b) and neutral (c) conditions at $T = 80^\circ\text{C}$ for 23 h contact time and an initial amount of 500 mg/L, using an UPLC/UV method on a BEH C18 column ($1.7\ \mu\text{m}$, $2.1\ \text{mm} \times 100\ \text{mm}$) (Waters). Mobile phases: acetonitrile- ammonium hydrogencarbonate ($\text{pH} = 8.2$; 10 mM) -35:65, v/v). Flow rate: 0.4 mL/min. Wavelength: 211 nm. Column temperature: 45°C .

180 Direct UV-vis spectrophotometric method shows that quinapril and its by-products present similar UV spectra
181 with a benzenoid profile (Appendix A, Fig. A.1). These spectra are characterized by weak shoulders at high
182 wavelength values (> 250 nm). It can be therefore concluded that this method was not suitable, neither for
183 qualitative nor quantitative analysis of quinapril in a mixture of potential degradation products, since it caused a
184 problem of interference. To overcome this problem, due to degradation products other than analytes derivative
185 spectroscopy can be used as a qualitative and quantitative method [37-39]. On the other hand, this technique
186 proved its ability for analysis of benzenoid drugs such as ACE-inhibitors [39] whose UV spectra exhibit a partial
187 fine vibrational structure.

188 In order to investigate the ability of derivative spectrophotometric methods to measure the quinapril response in
189 the presence of all the potential by-products, the derivative mode 1D , 2D , 3D and 4D (first, second, third and
190 fourth-order derivative spectra), followed by currently used UPLC-DAD method were therefore plotted against
191 wavelength. The degree of derivation was chosen in order to improve the resolution and the sensitivity of
192 overlapping absorption and to find differences between UV spectra shapes of quinapril and its by-products. As
193 can be seen from (Appendix A, fig.A.2), the derivation process allowed the conversion of large bands to sharp
194 and intense peaks. Derivative UV spectra of quinapril and its by-products were quite similar and presented the
195 same maximum of absorption except the degradation product eluted at 0.53 min. For instance, the second-order
196 UV spectra of quinapril and its by-products exhibited intense peaks. As a result, derivative UV
197 spectrophotometric method cannot be applied for quantitative or qualitative analysis of quinapril in the presence
198 of its degradation products, due to the interference that can occur. In conclusion, the characteristic profile of the
199 derivative spectra may not constitute a specific method useful to confirm drug identity and purity; no decrease in
200 the amount of quinapril can be observed owing to its interference with degradation products.

201 In spite of the similarity of UV visible absorption and response factor of related compounds, their MS ionization
202 efficiencies can be significantly different. The target degradation products under study have been therefore
203 differentiated thereafter as DPx for acidic and neutral conditions and DPxb for alkaline medium.

204 **3.2. Identification of degradation products of quinapril by UPLC-MS/MS**

205 UPLC-MS/MS has become a powerful technique to determine drugs in various matrix, specific fragmentation
206 pattern give selectivity and sensitivity and allow the accurate determination of numerous drugs such as ACEI
207 [31][40]. The use of UPLC-MS/MS is particularly relevant for the elucidation of impurities and degradation
208 product structures and to propose degradation mechanisms [41-43]. Last years, many studies have employed the
209 LC-MS/MS technique in order to evaluate ACEI stability and to characterize their degradation products [42, 44-

210 45]. In order to elucidate the structure of degradation products induced by thermal hydrolysis process, LC-MS
211 and LC-MS/MS substructural analysis methods have been therefore developed. These methods include
212 information on molecular structures, chromatographic behaviour, molecular weight and MS/MS substructural
213 information.

214 Using ammonium hydrogencarbonate as the mobile phase, the chromatographic method previously described
215 was directly transferred from LC-DAD to LC-MS/MS. Due to its volatility, ammonium hydrogencarbonate is
216 being an essential buffering specie for rapid LC-MS product identification [33]. However, formation of
217 ammonium adducts could make more complex the MS/MS interpretation [40]. In a first time, full-scan UPLC-
218 MS/MS of the degradation mixture ($[QUI]_0 = 500 \text{ mg/L}$; $[HCl] = 0.1 \text{ M}$; contact time = 23 h; $T = 80^\circ\text{C}$) has been
219 performed and showed that retention times observed for quinapril and the major degradation products were close
220 to those obtained by LC-DAD.

221 MS spectra were acquired for each chromatographic peak. To further elucidate the structure of these degradation
222 products, the MS/MS spectra (Appendix B, fig B.1 and fig B.2) of these products were acquired in an additional
223 run with collision energy of 20 eV. This enabled to determine the elemental composition for the product ions of
224 degradation products. The observed m/z values for molecular ion peak and major fragments of the quinapril and
225 its degradation products under acidic and neutral media are listed in Table.1. These results prove that the same
226 by-products were obtained under acidic and neutral conditions, with m/z values equal to m/z 252 (DP1), 178
227 (DP2), 280 (DP3), 393 (DKPA), and 421(DPK). It should be noted that ammonium adducts $[M+NH_4]^+$ was not
228 observed.

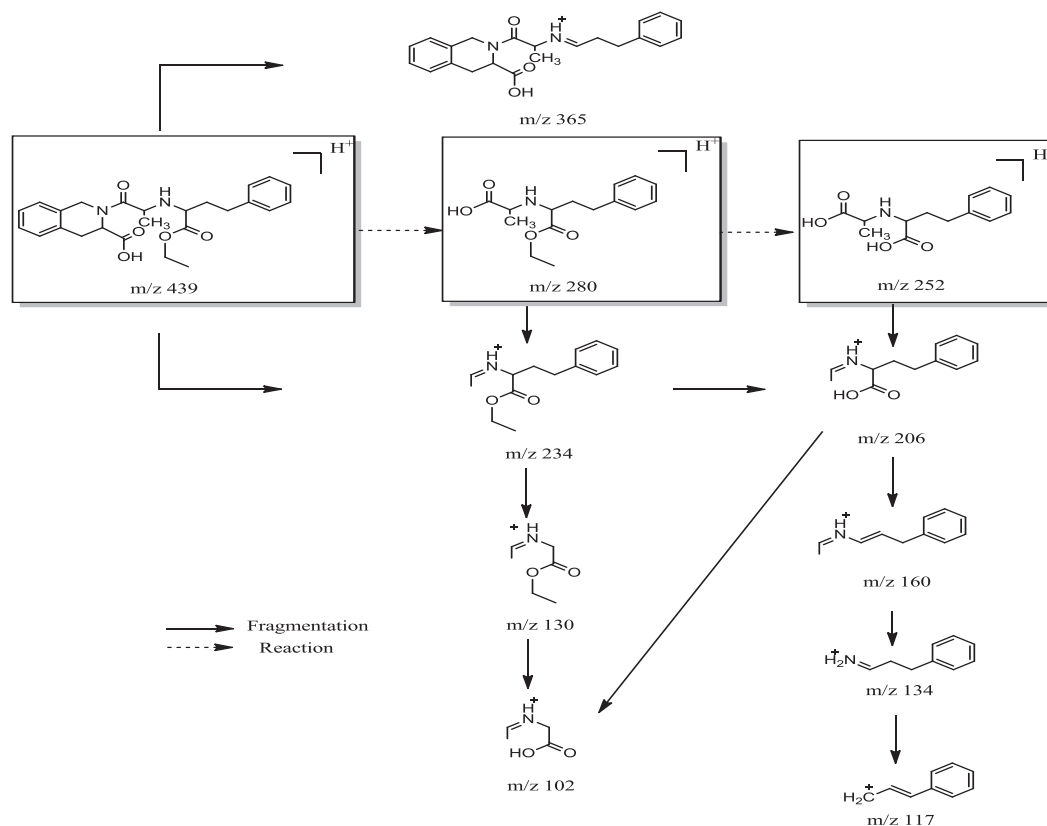
229 **Table 1.** Observed m/z values for the [M+H]⁺ ions and major fragments of quinapril and its by- products in
 230 acidic, neutral and alkaline media.

Degradation products	Retention time (min)	[M+H] ⁺	Fragment ion	Fragment ion intensity (%)	Proposed elemental composition
DP1	0.53	252	206	100	C ₁₂ H ₁₆ NO ₂
			160	19	C ₁₁ H ₁₄ N
			117	15	C ₉ H ₉
			102	30	C ₄ H ₈ NO ₂
			91	5	C ₇ H ₇
DP2	0.68	178	132	100	C ₉ H ₁₀ N
DP3	0.74	280	234	50	C ₁₄ H ₂₀ NO ₂
			206	100	C ₁₂ H ₁₆ NO ₂
			160	13	C ₁₀ H ₁₂ NO ₂
			130	10	C ₁₁ H ₁₄ N
			117	25	C ₉ H ₉
			91	5	C ₇ H ₇
DKPA	0.93	393	375	60	C ₂₃ H ₂₃ N ₂ O ₃
			347	10	C ₂₂ H ₂₃ N ₂ O ₂
			319	5	C ₂₁ H ₂₃ N ₂ O
			231	70	C ₁₃ H ₁₄ N ₂ O ₂
			117	100	C ₉ H ₉
			91	1	C ₇ H ₇
Quinapril	1.37	439	365	8	C ₂₂ H ₂₅ N ₂ O ₃
			234	78	C ₁₄ H ₂₀ NO ₂
			206	2	C ₁₂ H ₁₆ NO ₂
			160	4	C ₁₁ H ₁₄ N
			130	5	C ₆ H ₁₂ NO ₂
			117	3	C ₉ H ₉
			102	2	C ₄ H ₈ NO ₂

DKP	8.92	421	375	95	$C_{23}H_{23}N_2O_3$
			347	13	$C_{22}H_{23}N_2O_2$
			319	5	$C_{21}H_{23}N_2O$
			231	100	$C_{13}H_{14}N_2O_2$
			117	50	C_9H_9
			91	2	C_7H_7
PD2b	0.55	411	365	2.5	$C_{22}H_{25}N_2O_3$
			206	30	$C_{12}H_{16}NO_2$
			178	3.75	$C_{10}H_{13}NO_2$
			160	1	$C_{11}H_{14}N$
			102	2	$C_4H_8NO_2$
PD1b	0.67	411	365	2.5	$C_{12}H_{16}NO_2$
			206	31	$C_{10}H_{13}NO_2$
			178	4	$C_{11}H_{14}N$
			160	0.5	$C_4H_8NO_2$
			102	1	$C_4H_8NO_2$
PD1'b	0.76	411	365	2.5	$C_{22}H_{25}N_2O_3$
			206	32	$C_{12}H_{16}NO_2$
			178	2.5	$C_{10}H_{13}NO_2$
			160	1.25	$C_{11}H_{14}N$
			102	1	$C_4H_8NO_2$

231 In order to elucidate the structures of quinapril by-products, the first step was to understand the fragmentation
232 pattern of the parent-drug substance. Indeed, the detailed mass spectrometry analysis of the fragmentation
233 pattern of quinapril provides a basis for assessing structural assignment for the degradation products. As can be
234 seen from Table 1, the fragmentation pattern for drug displayed the same behavior as reported by Burinsky and
235 Sides [31] and Vikas shinde et al [2]. Indeed, the (+) ESI-MS/MS spectrum of quinapril, with a protonated
236 molecular ion at m/z 439, showed a series of fragment ions of m/z values of 365, 234, 170, 160, 134, 130 and
237 117. The fragment ion with m/z 365, which was 74 Da less than the quinapril ion, resulted from the loss of the
238 ester side chain ($OCOCH_2CH_3$). The most intense fragment at m/z 234 resulted from the cleavage of the bond

239 between the carbon atom of the amide group and the α -carbon, followed by further loss of $\text{CH}_2=\text{CH}_2$ to yield m/z
 240 206 and subsequent elimination of styrene to produce m/z 102. Finally, the subsequent fragments at m/z 160,
 241 134 and 117 originated from the aliphatic chain reduction from the product-ion m/z 206 (Fig. 2).



242
 243 **Fig. 2.** Fragmentation pattern for quinapril (m/z 439) and some degradation products; DP3 (m/z 280)
 244 and DP1 (m/z 252)

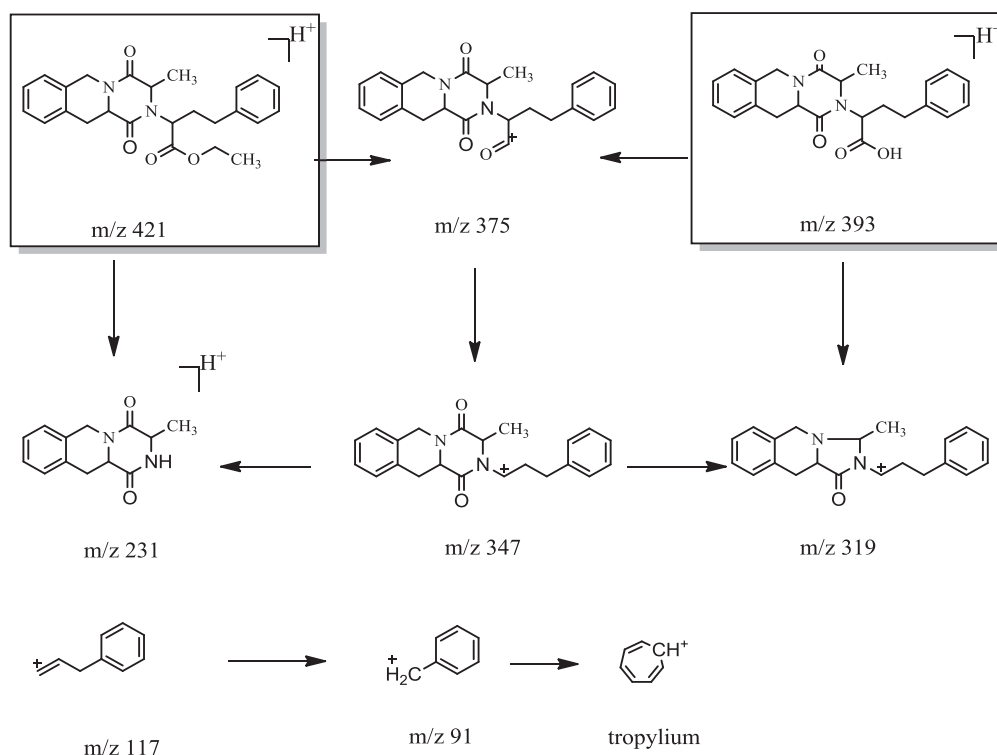
245 According to the structure of quinapril, cyclization, ester and amide bond hydrolysis were the possible
 246 degradation pathway that can be foreseen. However, from Table 1 only two major degradation pathways of
 247 quinapril in acidic and neutral media were observed; cyclization was the main pathway, while hydrolysis of the
 248 amide bond was only observed at low levels in the samples.

249 The degradation product eluted at 8.92 min retention time, exhibited the same MS^1 spectrum with a molecular
 250 ion at m/z 421, both under acidic and neutral conditions. The MS^2 spectrum obtained by fragmentation of the
 251 m/z 421 ion led to a series of atypical ions (m/z 375, 347, 319, 231, 117, 91) (Fig.3) compared to quinapril
 252 fragmentation. With respect to the MS^2 spectrum (Appendix B, Fig. B.3), the mechanism of fragmentation
 253 presented in fig. 4 can be suggested from the diketopiperazine product (DKP). Formation of the diketopiperazine
 254 product requires deprotonation of the reacting amine followed by the addition of neutral nitrogen to the carbonyl
 255 of the neighboring carboxylic acid to form a tetrahedral intermediate, which then loses water to give the
 256 diketopiperazine product. Similar results were observed for some ACE inhibitors such as moexipril [46],

257 enalapril [47], lisinopril [48], ramipril [46, 49], xpril and perindopril [50] which yield to the diketopiperazine
258 product under acidic and neutral conditions.

259 The compound eluted at a retention time of 0.93 min with a protonated molecular m/z 393 was 28 Da less than
260 quinapril diketopiperazine. 28 Da corresponded to the loss of $\text{CH}_2=\text{CH}_2$ to yield to the diketopiperazine acid
261 product ($\text{C}_{23}\text{H}_{24}\text{N}_2\text{O}_4$). This product characterized by the same fragment ions as quinapril diketopiperazine, can
262 result from the hydrolysis of the ester function of DKP or cyclization of the diacid product with an m/z value of
263 411. However, the diacid product of quinapril was not detected both in neutral and acidic media. In order to
264 confirm that the diacid product of quinapril with m/z value of 411 is not coeluted, a LCMS¹ attempts were made
265 to follow the "LC/MS profile" of this compound ($m/z=411$). Results obtained proved that this product was not
266 detected neither in acid medium nor neutral medium.

267 The last hypothesis was a direct transformation of the diacid product to yield DKPA. A simulation study could
268 be later considered to confirm or deny this assumption.



269

270 **Fig. 3.** Fragmentation pattern for degradation products DKP and DKPA with m/z 421 and 393,
271 respectively

272 The second possible pathway of degradation, namely a hydrolysis of the amide bond, was confirmed by the
273 presence of two degradation products DP2 and DP3 with protonated molecular $[\text{M}+\text{H}]^+$, m/z 178 and 280, both

274 in neutral and acidic media. This result was in agreement with other findings [51-52], showing that the cleavage
275 of the peptide bond is a common degradation pathway of peptides and proteins. Based on the MS² spectra
276 (Appendix B, Fig. B.3), the elemental composition for these ions were C₁₀H₁₁NO₂ and C₁₅H₂₁NO₄ for m/z 178
277 and 280, respectively. The DP3 with an m/z value of 280 was characterized by a series of fragments 234, 206,
278 160, 130, 117, 91. The most intense fragment (m/z 206) corresponded to the loss of 74 Da relative to the ester
279 function followed by further loss of formic acid (46 Da). Furthermore, the other fragments at m/z 130, 117 and 91
280 were characteristics of intact part of the molecule (C₉H₁₂N). Except the fragment ion m/z 130, the by-product
281 DP1, which differed from DP3 by 28 Da, displayed the same fragment ions characteristic of the intact part. 28
282 Da corresponded to a loss of an ethyl group generated by hydrolysis of an ester function. According to the
283 elemental composition of this product, it can be assumed that this diacid product can be derived from the
284 cleavage of the amide bond of the active metabolite quinaprilat or the hydrolysis of the ester function of the DP3
285 by-product with m/z 280 (fig.2).

286 These results seem to be in accordance with some studies showing that cyclization and amide bond hydrolysis
287 occurred under acid and neutral conditions. In fact, it is well documented in the literature that dipeptides and
288 proteins readily cyclize to diketopiperazine derivate and underwent a hydrolysis of the amide bond [51] [53].
289 The present work also shows that the rate of cyclization competes favorably with hydrolysis, in agreement with
290 previous findings dealing with the forced degradation of some ACEI, namely fosinopril and enalapril maleate
291 [52, 47]. These studies proved that the main decomposition route was the internal aminolysis reaction, producing
292 the diketopiperazine and that the amide bond tends to cleave in acidic and neutral media. However, under these
293 conditions ramipril and moexipril yield only the DKP product [48].

294 Because very low amounts of DP3 and DP4 were observed during the thermal hydrolysis, it is inferred that
295 hydrolysis of this bond was slower than the formation of diketopiperazine. It is in agreement with earlier
296 investigations showing that internal aminolysis of dipeptide methyl esters and amides to form diketopiperazine
297 was much faster than the hydrolysis of ester and amide functionalities [53].

298 The exclusive formation of by-products with m/z 411 under alkaline conditions was in agreement with previous
299 investigations which demonstrated that the ester function of enalapril maleate, ramipril and moexipril undergo
300 hydrolysis to yield the dicarboxylic form of ACEI [47-48]. MS² analysis of these by-products shows the same
301 ion fragments (365, 206, 178, 160, 102). These products are relative to the quinaprilat and its isomers. The DP1b
302 was characterized by a peak splitting, most likely due to the presence of the two conformers s-cis and s-trans
303 around the amide bond N-C=O. Analysis by LC/MS and LC/DAD confirmed that the peak splitting was due to

304 the presence of two conformers. In fact, the purity of the peak relative to quinaprilat was checked by comparing
305 the UV spectra and by examination of the MS spectra. In addition, the effect of various operating conditions on
306 the retention peak, namely splitting and bond broadening of quinaprilat and quinapril, have been qualitatively
307 examined. This study provided more practical experimental conditions, allowing both the elution of quinaprilat
308 and quinapril as single peaks, while keeping at the same time an acceptable separation. The effect of various
309 factors on the conformational equilibrium s-cis/s-trans of quinapril and quinaprilat, namely the composition of
310 the mobile phase, flow rate, and column temperature was investigated and the results are shown in the supporting
311 information. The degradation product eluted at 0.55 min retention time shows the same fragmentation pattern as
312 quinaprilat and can result from the epimerization of the DP1; about 25% of the observed degradation in 0.01 N
313 NaOH was epimerized (Fig. 1.a). However, due to the lack of authentic isomers (RSS, SRR, SRS), the nature of
314 the epimer cannot be elucidated.

315 Similar results have been reported on moexiprilat degradation in 0.1 N KOH by Gu et al [54].

316 **3.3 Mechanism and kinetic of quinapril degradation**

317 Structural elucidation of by-products led to the proposal of the degradation mechanism given in Fig. 4. It is
318 postulated that cyclization is the major degradation process of quinapril under acidic and neutral conditions.
319 Formation of diketopiperazine is followed by the hydrolysis of the ester function to lead to the diketopiperazine
320 acid. Cleavage of the amide bond constitutes the second pathway of degradation of quinapril. In fact, the amide
321 bond undergoes hydrolysis to lead to the two by-products DP3 and DP2 with m/z 280 and 178 respectively. Thus
322 the DP1 by-product is generated from the hydrolysis of the ester function of DP3. Therefore, quinapril undergoes
323 hydrolysis of the ester function only under alkaline conditions.

324 In order to check the possibility of cyclization of quinaprilat to yield DKPA, two successive reactions were
325 performed. These reactions consisted of an alkaline hydrolysis (NaOH 0.01 N) of quinapril at 80 °C, until the
326 started material was exhausted, followed by an acidic hydrolysis (HCl 0.1N) at the same temperature. Analysis
327 of the chromatographic profile of quinaprilat under acidic conditions by LC/DAD and LC/MS shows that DKPA
328 was the major by-product formed. The kinetic study by the chromatographic method shows that the constant
329 rate of the formation of DKPA was $3.9 \cdot 10^{-3} \text{ h}^{-1}$.

341 shows a typical time course of disappearance of quinapril and formation of its major degradation products
 342 detected under the studied media. Main products were quinaprilat and its isomers products in alkaline medium,
 343 and both DKP and DKPA in acid and neutral media. Accordingly, cyclization of quinapril was much faster than
 344 hydrolysis of amide and ester bonds under acidic and neutral media.
 345 As quinaprilat and quinaprilat isomers were only formed under basic medium, only the ester bond hydrolysis
 346 was considered. In all conditions, quinapril concentration decreased exponentially with time and since
 347 hydrochloric acid, water and sodium hydroxide are in large excess with respect to quinapril, the kinetics would
 348 be a typical pseudo-first-order process. This kinetic behaviour was compatible with earlier reports for other ACE
 349 inhibitors, such as enalapril maleate [50] [55], xpril, perindopril [50] [56], benazepril [57] and moexipril [12].

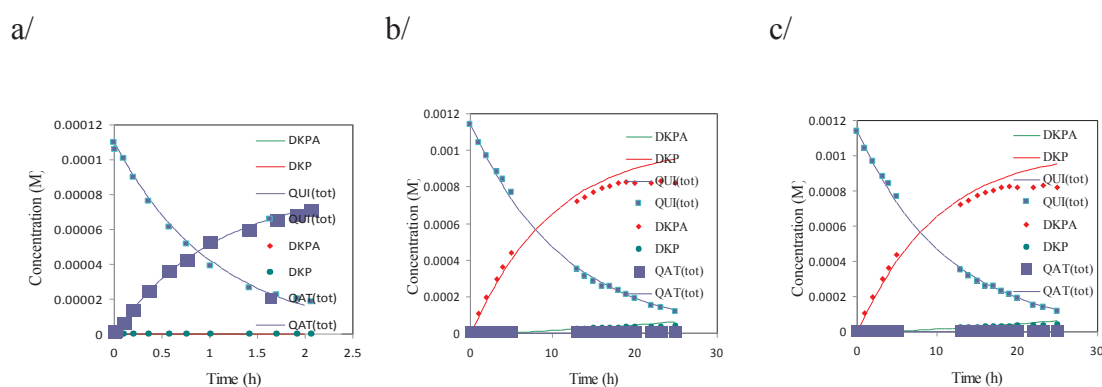


Fig. 5. Degradation of quinapril ($[QUI]_0 = 500 \text{ ppm} = 1.14 \text{ mM}$) at $T = 80 \text{ }^\circ\text{C}$ under alkaline (a), acidic (b) and neutral (c) conditions. Experimental concentration-time profiles for quinapril, and diketopiperazine product (left axis) and degradation product (m/z 393) (right axis)

350 Fig.6 confirmed that at 80°C quinapril degraded faster under alkaline conditions compared to acidic and neutral
 351 conditions. The apparent first-order degradation rate constants at 80°C were calculated and found to be 0.19 h^{-1}
 352 ($t_{1/2} = 3.70 \text{ h}$), 0.086 h^{-1} ($t_{1/2} = 8.02 \text{ h}$) and 1.12 h^{-1} ($t_{1/2} = 0.62 \text{ h}$) for acidic, neutral and
 353 alkaline degradation processes, respectively. These results proved that quinapril was more stable under neutral
 354 conditions, in agreement with previous works dealing with enalapril maleate [41], xpril and perindopril [37][44],
 355 and benazepril [50].

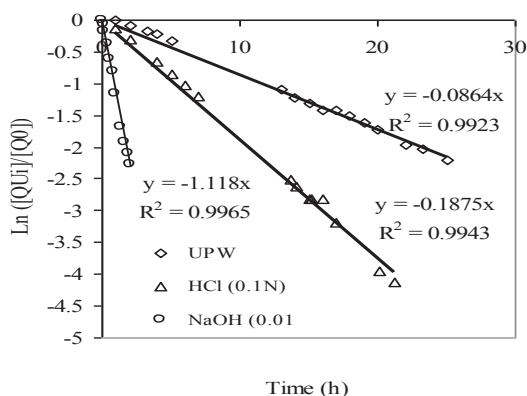


Fig. 6. First-order plots for the rate of disappearance of quinapril under alkaline, acidic ($[HCl] = 0.1\text{ M}$) and neutral conditions ($[QUI]_0 = 500\text{ ppm} = 1.14\text{ mM}$ at 80°C).

356 3.5. Degradation pathway of quinapril

357 Kinetic model was developed according to the proposed degradation pathway of quinapril under all
 358 consideration media. Only the main product (quinaprilat, DKP and DKPA) were considered in the kinetic model.
 359 COPASI 4.8 [58] was used to calculate the rate constant from the experimental data point and to simulate the
 360 degradation curves of quinapril and the formation of DKP and DKPA. In order to fit the rate constants to
 361 experimental data, it was assumed that the molar extinction coefficient of quinapril and its by products were
 362 similar. Because cyclisation of quinapril or quinaprilat to form DKP or DKPA requires the protonation of the
 363 carboxylic formation, acid-base equilibria of quinapril and quinaprilat were considered. Rate constant were
 364 determined by the least square method using the evolutionary programming method for parameters optimization
 365 using COPASI software. Degradation rate constant of quinapril to form quinaprilat and quinaprilat isomers was
 366 determined by considering only the experiment under alkaline conditions. Other degradation rate constants (k_1 ,
 367 k_2) were evaluated with multiple experimental parameters (estimation formation considering experimental data
 368 point from acid and neutral conditions). Values and SD obtained for the kinetic rate constant were reported in
 369 fig. 4. A complete model including degradation pathway observed under all tested conditions was then
 370 developed and used to simulate the degradation curves of quinapril and the formation of the main by-products
 371 (Fig. 5). The proposed kinetic model allowed an accurate description of quinapril degradation.

372 Modelling the degradation curves to the equation rates that describe the reaction pathways proposed allowed to
 373 check the assumption given in fig.4. Curves (in continuous lines) under neutral and acidic media are given in fig.
 374 5. The rate constants of disappearance of quinapril and the appearance of quinapril DKP, quinapril DKPA and
 375 quinaprilat were fitted. Pseudo-first-order kinetics were observed in all cases, and the rate constants (k_1 and k_2)

376 were determined and found to be $0.177 \pm 0.001 \text{ h}^{-1}$, $3.79 \cdot 10^{-3} \pm 1.04 \cdot 10^{-3}$, respectively. However quinaprilat was not
377 formed, neither under acidic medium nor under neutral medium. So, $k_1[\text{QH}]$ was far superior to $k_3[\text{Q}^-]$ (QH and
378 Q^- are respectively the protonated and unprotonated forms of quinapril respectively). Therefore, the DKPA
379 formed during the degradation of quinapril must result from the hydrolysis of DKP rather than from the
380 cyclization of quinaprilat. It was consistent with previous investigations demonstrating that ester and amide
381 functional groups of dipeptides undergo intramolecular aminolysis at a much faster rate than hydrolysis [51].

382 **Conclusion**

383 The development of a stability-indicating UPLC assay method for quinapril allowed the separation of the drug
384 and its by-products formed under various stress conditions.

385 Quinapril was found to be unstable in solution showing the formation of five degradation products. Structural
386 elucidation performed by UPLC-MS-MS confirmed the presence of known by-products and allowed to propose
387 the structure of unknown products. Comparison of the stability of quinapril under solution and solid states
388 showed that kinetics and by-products distribution were altered.

389 Through detailed kinetic study and by-products distribution a complete model including degradation pathway
390 observed under all tested conditions was developed.

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