

*Novel antioxidant and anti-inflammatory peptides from the Siamese crocodile (Crocodylus siamensis) hemoglobin hydrolysate*

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1 **Novel antioxidant and anti-inflammatory peptides from the Siamese crocodile**  
2 **(*Crocodylus siamensis*) hemoglobin hydrolysate**

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20 **Running title:** Bioactive peptides from *C. siamensis* hydrolysates

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31 **Abstract** Novel antioxidant and anti-inflammatory peptides were isolated from hydrolysates of Siamese  
32 crocodile (*Crocodylus siamensis*) hemoglobin. *Crocodylus siamensis* hemoglobin hydrolysates (CHHs) were  
33 obtained by pepsin digestion at different incubation times (2, 4, 6 and 8 H) at 37 °C and subjected to antioxidant  
34 and anti-inflammatory activity assessment. CHH obtained by 2-H hydrolysis (2H-CHH) showed the highest  
35 anti-inflammatory activity with respect to decreasing nitric oxide (NO) production, while the strongest  
36 antioxidant activity was found for 6-H hydrolysis (6H-CHH) against nitric oxide radicals. To evaluate the anti-  
37 inflammatory and antioxidant activity of individual peptide components, 2H-CHH and 6H-CHH were purified  
38 by semi-preparative HPLC. Peptide fraction P57 isolated from 6H-CHH was found to exhibit the highest nitric  
39 oxide radical inhibition activity (32.0%). Moreover, purification of 2H-CHH yielded peptide fraction P16,  
40 which displayed a high efficacy in decreasing NO production of macrophage RAW 264.7 cells (83.2%) and  
41 significantly reduced pro-inflammatory cytokines and inflammatory mediators interleukin-6 (IL-6), interleukin-  
42 1 beta (IL-1 $\beta$ ) and prostaglandin-E2 (PGE<sub>2</sub>) production to about 2.0, 0.3 and 1.9 ng/mL, respectively. Using  
43 LTQ orbitrap XL mass spectrometry, active peptide sequences were identified as antioxidant KIYFPHF (KF7),  
44 anti-inflammatory SAFNPHEKQ (SQ9) and IIHNEKVQAHGKKVL (IL15). Additionally, CHHs simulated  
45 gastric and intestinal *in vitro* digestion positively contributed to antioxidant and anti-inflammatory activity.  
46 Taken collectively, the results of this work demonstrate that CHHs contain several peptides with anti-  
47 inflammatory and antioxidant properties which may prove valuable as treatment or supplement against diseases  
48 associated with inflammation and oxidative stress.

49

50 **Keywords:** *Crocodylus siamensis*, enzymatic hydrolysis, hemoglobin hydrolysate, inflammation, oxidative stress,  
51 purification and identification

52

53 **Abbreviations:** CHHs, *Crocodylus siamensis* hemoglobin hydrolysates; cHb, *C. siamensis* hemoglobin; COX-2,  
54 cyclooxygenase-2; DH, degree of hydrolysis; IL-1 $\beta$ , Interleukin 1 beta; IL-6, Interleukin 6; NO, Nitric oxide;  
55 PGE<sub>2</sub>, Prostaglandin E2; TNF- $\alpha$ , Tumor necrosis factor alpha.

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## 61 **1. Introduction**

62 Inflammation, oxidative stress and free radical damage have recently been acknowledged as a global threat for  
63 human health. Albeit being common by-products of a broad range of processes ensuring cellular homeostasis,  
64 excessive generation of radical metabolites is unambiguously associated with a variety of serious disorders such  
65 as cancer, heart disease, strokes, Alzheimer's, and premature aging [1]. Similarly, the inflammatory response  
66 constitutes an important natural reaction of the host defense system to injury and the invasion of toxins or  
67 infectious particles. In the case of pathogenic infection, inflammation contributes to combatting the disease and  
68 protecting vital parts of the body, while suspending the normal immune response and shunting certain metabolic  
69 pathways at the same time. Specific pro-inflammatory mediators and cytokines, such as NO, PGE<sub>2</sub>, TNF- $\alpha$ , IL-  
70 1 $\beta$  and IL-6, comprise vital parts of the inflammatory cascade and are generated to affect immune cell function  
71 as well as proliferation activity [2]. In the long term, however, inflammatory processes are known to result in  
72 progressive damage and are usually associated with excessive free radical release and oxidative stress [3].

73 The latter is defined as an inequality between the free radicals production and reactive metabolites resulting  
74 in damage to cells and important biomolecules which severely impacts all organisms [4]. Free radicals, which  
75 account for the majority of both reactive nitrogen species (RNS) and reactive oxygen species (ROS), are defined  
76 as molecular species possessing one or more non-bonding paired electrons in spatially different orbitals of atoms  
77 or molecules [5]. Also, they have high potential to either donate an electron to or accept an electron from other  
78 molecules, consequently behaving as oxidants [6]. The latter process is capable of inflicting severe damage to  
79 the membranes and nuclei of cells by oxidizing important biochemical molecules such as proteins, lipids,  
80 carbohydrates, and DNA [7]. During the course of the inflammation high amounts of free radicals are produced  
81 within the inflamed tissue, in particular NO, which acts as a major pro-inflammatory mediator in the human  
82 body and is generated from macrophage in response to the inflammation [8]. In this context NO is generally  
83 regarded as the key mediator correlating inflammation and oxidative stress. The discovery and development of  
84 substances capable of inhibiting either the activity or production of NO has therefore gained considerable  
85 attention within the recent years as they may be utilized to reduce the detrimental effects of both inflammation  
86 and oxidative damage.

87 *Crocodylus siamensis*, commonly called Siamese crocodile, is a small freshwater crocodylian populating  
88 parts of Southeast Asia, including Thailand. Recently, several components of *C. siamensis* blood, i.e. plasma,  
89 serum, white blood cells and hemoglobin have been reported to possess a broad spectrum of biological  
90 properties, mainly attributed to abundance of a number of biologically active peptides and proteins. Among

91 these, hemoglobin constitutes the most abundant component and has been shown to exhibit antimicrobial [9],  
92 antioxidant [10, 11] and anti-inflammatory activity [11, 12].

93 In addition to the direct extraction of specific proteins with desired biological activity, enzymatic hydrolysis  
94 of protein sources has been established as a convenient method to generate novel protein fragments with  
95 enhanced biological properties. A variety of animal proteins was shown to be applicable for producing bioactive  
96 peptides via protein hydrolysis within recent decades, granting access with specific properties of interest such as  
97 inhibitory activity on angiotensin I converting enzyme [13-16], antibacterial activity [17], antioxidant activity  
98 [18, 19] and anti-inflammatory activity [20]. In this context, it is anticipated that the biological properties of *C.*  
99 *siamensis* blood proteins and their potent antioxidant and anti-inflammatory activity may be further enhanced by  
100 protein hydrolysis.

101 As a consequence, this study aimed to investigate the antioxidant and anti-inflammatory peptides from *C.*  
102 *siamensis* hemoglobin hydrolysates (CHHs) derived by pepsin digestion. NO scavenging, linoleic peroxidation  
103 and ferric reducing power assays were conducted to determine the antioxidant activity of the CHHs, whereas  
104 MTT, NO (of macrophage RAW 264.7 cells), IL-6, IL-1 $\beta$  and PGE<sub>2</sub> assays were used to investigate the anti-  
105 inflammatory activity. *In vitro* digestion and hemolytic activity were used to determine the application uses.  
106 Furthermore, the identity of the antioxidant and anti-inflammatory peptides was elucidated via amino acid  
107 sequence determination using ultra-high performance liquid chromatography-LTQ orbitrap XL mass  
108 spectrometry.

109

## 110 **2. Materials and Methods**

### 111 **2.1. Materials and reagents**

112 RPMI 1640 medium, antibiotic/antimycotic (penicillin/streptomycin/amphotericin B), trypsin-EDTA and fetal  
113 bovine serum (FBS) were purchased from Gibco (USA). Pepsin from porcine gastric mucosa, picrylsulfonic  
114 acid solution (TNBS), sodium sulfite, L-leucine, ammonium thiocyanate, ferrous chloride, potassium  
115 hexacyanoferrate, ferric chloride, Linoleic acid, 6-hydroxy-2,5,7,8-tetramethylchroman-2-carbonic acid  
116 (Trolox), glutathione (GSH), 2,20-azobis-(2-amidinopropane)-dihydrochloride (ABAP), dimethyl sulfoxide  
117 (DMSO), lipopolysaccharide (LPS), NaCl, HCl, PBS, bile salts solution, pancreatin solution, CaCl<sub>2</sub>, Triton X-  
118 100 were purchased from Sigma-Aldrich (Germany). Sodium nitroprusside was purchased from Merck  
119 (Germany). 3-(4,5-diamethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) was purchased from Eugene  
120 (USA).

## 121 **2.2. Crocodile hemoglobin preparation**

122 Crocodile blood was collected from a slaughterhouse (Srirachamoda Co., Ltd.) in Thailand, and the extraction of  
123 hemoglobin from red blood cells was performed following the method of Srihongthong et al. [9]. Blood was  
124 collected and transferred to 15 mL sterile tubes containing 0.08 g of EDTA. Blood samples were stored at 4 °C  
125 overnight to allow blood cells to settle. Red blood cells (bottom layer) were collected in sterile tubes after  
126 elimination of plasma (top layer) and white blood cells (middle layer). Isolated red blood cells were washed  
127 three times with phosphate buffer saline (PBS), pH 7.0, and centrifuged at 3,000g for 5 min at 4 °C. Ice-cold  
128 distilled water of five-fold volume was added to the RBC pellet, followed by vigorous mixing and allowing the  
129 mixture to settle for 10 min. After centrifugation at 10,000g for 20 min at 4 °C, the supernatant was collected for  
130 lyophilization and then stored at -70 °C.

131

## 132 **2.3. Enzymatic hydrolysis**

133 Enzymatic hydrolysis was performed according to the method of Yu et al. [21]. Shortly, the hemoglobin  
134 solution was digested by pepsin with a ratio of enzyme to substrate of 1:100 (w/w) at 37 °C for 2, 4, 6 and 8 H  
135 and boiled at 95 °C for 10 min to quench the reaction by inactivating the enzyme. The hydrolysis condition of  
136 hemoglobin by pepsin was performed at pH 2.0 (adjusted with 1 M HCl), followed by removal of insoluble  
137 components by centrifugation at 7,168g for 20 min. The supernatant was collected and adjusted to pH 7.0 by  
138 addition of 1 M HCl or 1 M NaOH. Finally, the supernatants of the crocodile hemoglobin hydrolysates (CHHs)  
139 were lyophilized and stored at -20 °C.

140

## 141 **2.4. Degree of hydrolysis**

142 The degree of hydrolysis was determined following the method of Benjakul et al. [22]. Briefly, 125 µL of CHHs  
143 were added to 2.0 mL of 0.21 M sodium phosphate buffer, pH 8.2, followed by addition of 1 mL of 0.01%  
144 TNBS solution. The mixture was incubated in a water bath at 50 °C for 30 min in the dark, and 2 mL of 0.1 M  
145 sodium sulfite was added to stop the reaction. The mixture was then allowed to cool for 15 min. The absorbance  
146 was measured at 420 nm and the  $\alpha$ -amino acid content expressed in terms of L-leucine. The percentage of the  
147 degree hydrolysis was calculated using the formula:

$$148 \text{ DH} = [(L_t - L_0)/(L_{\text{max}} - L_0)] \times 100$$

149 where  $L_0$  determines the amount of  $\alpha$ -amino acid expressed in the sample.  $L_t$  corresponds to the amount of  $\alpha$ -  
150 amino acid released at time  $t$ .  $L_{max}$  determines the maximum amount of  $\alpha$ -amino acid after hydrolysis by 5 M  
151 HCl at 100 °C for 24 H.

152

### 153 **2.5. Nitric oxide (NO) scavenging assay**

154 Nitric oxide (NO) was generated from sodium nitroprusside and measured using Griess reagent. The assay was  
155 conducted according to the method of Yen et al. [23] with modifications. For the experiment, 250  $\mu$ L sodium  
156 nitroprusside (10 mM) in PBS were mixed with 15, 31, 62, 125, 250 and 500  $\mu$ g/mL of CHHs and incubated at  
157 25 °C for 2 H. An aliquot of the incubated solution (100  $\mu$ L) was added to 100  $\mu$ L of Griess reagent (1%  
158 sulfanilamide in 5% phosphoric acid and 0.1% naphthylethylenediamine dihydrochloride) and incubated in the  
159 dark for 10 min before measuring the absorbance at 540 nm. Butylated hydroxytoluene (BHT) was used as a  
160 positive control. All samples were analyzed in quadruplicate. The percentage of inhibition was calculated using  
161 the formula: % inhibition =  $[(Abs_{cont} - Abs_{test})/Abs_{cont}] \times 100$ .

162

### 163 **2.6. Linoleic peroxidation assay**

164 This assay was performed following the method of Ledesma et al. [24] with modifications. Briefly, 50  $\mu$ L of  
165 CHHs (0.005, 0.05, 0.5, 5, 50 and 500  $\mu$ g/mL) were added to 50  $\mu$ L of linoleic acid (0.05% v/v) solution. 0.07  
166 M ABAP (10  $\mu$ L) was added and the solution mixed for 10 min. After addition of 150  $\mu$ L 20% (v/v) acetic acid,  
167 the mixture was incubated at 70 °C for 1 H. Twenty microliter of each solution was then added to a 96-well  
168 plate already containing 75% ethanol (160  $\mu$ L), 15% ammonium thiocyanate (10  $\mu$ L) and 10 mM ferrous  
169 chloride (10  $\mu$ L). The new solution was mixed and incubated at for 3 min. The absorbance was measured at 500  
170 nm and Trolox used as positive control. All samples were analyzed in sextuplicate. The antioxidant activity was  
171 analyzed and the percentage of antioxidant inhibition (% AI) of each sample was calculated using the following  
172 formula:

$$173 \text{ \% AI (antioxidant inhibition) } = 100 \times [Abs_{cont} - Abs_{test}]/Abs_{cont}$$

174

### 175 **2.7. Ferric reducing power assay**

176 This assay was modified from the method of Girgih et al. [25]. Briefly, 250  $\mu$ L of CHHs (0.005, 0.05, 0.5, 5, 50  
177 and 500  $\mu$ g/mL) and positive control (glutathione) were added to 250  $\mu$ L of 0.2 M phosphate buffer, pH 6.6. 250  
178  $\mu$ L of 1% (w/v) potassium hexacyanoferrate solution were added, vortexed and the mixture incubated at 50 °C

179 for 20 min. The reaction was quenched by adding 250  $\mu\text{L}$  of 10% TCA and incubated for 10 min before  
180 centrifugation at 800g for 10 min. Aliquots of each solution (30  $\mu\text{L}$ ) were then transferred to a 96-well plate  
181 already containing double distilled water (160  $\mu\text{L}$ ) and 0.1% (w/v) ferric chloride (10  $\mu\text{L}$ ). The reaction mixture  
182 was homogenized and incubated at 25  $^{\circ}\text{C}$  for 10 min, followed by measuring the absorbance at 700 nm. All  
183 samples were analyzed in quadruplicate. The antioxidant activity for each sample was expressed as Trolox  
184 (mM) equivalents and calculated using the equation of the standard curve of the positive control.

185

## 186 **2.8. Cell culture**

187 A murine macrophage cell line (RAW 264.7) was purchased from the American Type Culture Collection  
188 (American Type Culture Collection [ATCC], USA) and cultured in RPMI 1640 medium supplemented with  
189 10% heat-inactivated fetal bovine serum (FBS), 100  $\mu\text{g}/\text{mL}$  of streptomycin, 100 U/mL of penicillin, 25  $\mu\text{g}/\text{mL}$   
190 amphotericin B and incubated at 37  $^{\circ}\text{C}$  in a 5%  $\text{CO}_2$  humidified atmosphere.

191

## 192 **2.9. Measurement of nitric oxide**

193 This assay was conducted according to the method of Phosri et al. [11]. CHHs (62, 125, 250 and 500  $\mu\text{g}/\text{mL}$ )  
194 were mixed with LPS (100  $\text{ng}/\text{mL}$ ), and the resulting solution incubated with RAW 264.7 cells. Another  
195 incubation was set up between LPS and RAW 264.7 cells at 37  $^{\circ}\text{C}$  in a 5%  $\text{CO}_2$  humidified atmosphere for 24  
196 H. 100  $\mu\text{L}$  of culture medium from each CHH sample were slightly mixed with 100  $\mu\text{L}$  of Griess reagent and  
197 incubated at 25  $^{\circ}\text{C}$  for 10 min. The absorbance was measured at 540 nm using a microplate reader (BioRad,  
198 Model 680, USA). Nitric oxide (NO) production was calculated as percentage of control. All samples were  
199 analyzed in quadruplicate.

200

## 201 **2.10. Cell viability**

202 Cell viability determination was performed using the MTT assay according to the method of Phosri et al. [11].  
203 RAW 264.7 cells ( $1 \times 10^5$  cells/mL) were cultured on a 96-well plate overnight. Lipopolysaccharides (LPS)  
204 were co-incubated with CHHs in defined concentrations (62, 125, 250 and 500  $\mu\text{g}/\text{mL}$ ) and 100  $\text{ng}/\text{mL}$  of LPS  
205 at 37  $^{\circ}\text{C}$  in a 5%  $\text{CO}_2$  humidified atmosphere. After incubation for 24 H the medium was discarded. MTT (3-  
206 (4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) (0.5  $\text{mg}/\text{mL}$ ) was added to RAW 264.7 cells and  
207 incubated at 37  $^{\circ}\text{C}$  in a 5%  $\text{CO}_2$  humidified atmosphere for 30 min before the medium was discarded. DMSO  
208 was added and the reaction mixture incubated at 25  $^{\circ}\text{C}$  for 30 min. The absorbance was measured at 570 nm and

209 the cell viability evaluated by comparing the absorbance with that of the control for each sample. All samples  
210 were analyzed in quadruplicate.

211

### 212 **2.11. Measurement of IL-6, IL-1 $\beta$ and PGE<sub>2</sub>**

213 Aliquots of culture medium employed in the NO assay were further used for determination of IL-6, IL-1 $\beta$  and  
214 PGE<sub>2</sub> expression using the ELISA kit and following the instructions in the manufacturer's manual (R&D,  
215 Minneapolis, MN, USA).

216

### 217 **2.12. Peptide purification from crocodile hemoglobin hydrolysates**

218 The purification of CHH was performed according to the method of Srihongthong et al. [9] with modifications.  
219 A HPLC system connected to a C-18 reverse phase column (10  $\times$  150 mm; Sunfire<sup>TM</sup> prep 5  $\mu$ m) was employed  
220 in the purification process. Fractions were separated using a mobile phase system consisting of mobile phase A  
221 (0.1% TFA in deionized water) and mobile phase B (60% acetonitrile in 0.1% TFA) with a flow rate of 1.0 mL/  
222 min. A gradient of 0-25% (v/v) B over 15 min, then 25-100% (v/v) B over 95 min was applied. The elution  
223 peaks were collected by monitoring the absorption at 220 nm. The antioxidant and anti-inflammatory activity of  
224 all peaks were assayed, followed by determination of the amino acid sequences for each peak showing  
225 significant biological activity.

226

### 227 **2.13. Amino acid sequence analysis**

228 The active fractions P16 of 2H-CHH and P57 of 6H-CHH were selected and the peptides identified using LTQ  
229 orbitrap XL Mass spectrometry employing the following search parameters: non-specified enzymatic cleavage  
230 with three possible missed cleavages, +/-0.8 Da mass tolerances for MS and MS/MS, a peptide mass tolerance  
231 of +/-5 ppm, methionine oxidation and Gln->pyro-Glu (N-term Q) variable modification, and monoisotopic  
232 mass. Data were additionally processed at the Mascot Server (<http://www.matrixscience.com/>) using MS/MS  
233 ion searches against SwissProt (current release).

234

### 235 **2.14. *In vitro* simulated gastric and intestinal digestion**

236 *In vitro* digestion models were used to simulate the condition of human stomach and intestine for observing  
237 remaining activity of CHHs as described by Cheong et al. [26] with modification. The ratio of sample: simulated  
238 gastric: simulated intestinal was 1: 1.5: 2. Simulated gastric solution was prepared by dissolving 2 g of NaCl, 7

239 mL of HCl and 3.2 g pepsin with DI up to 1 L. The pH was adjusted to 1.6 using 1 M HCl and maintained at 37  
240 °C in a temperature-controlled water bath (Julabo, Germany). Each CHHs were mixed and pH was adjusted to  
241 2.5 using 1 M HCl then incubated at 37 °C for 1 H. The simulated intestinal solution was prepared by mixing  
242 160 mL bile salts solution (5 mg/mL in PBS), 100 mL of pancreatin solution (4.8 mg/mL in PBS) and 40 mL of  
243 CaCl<sub>2</sub> solution (110 mg/mL in PBS). The pH was adjusted to 7 and maintained at 37 °C in a temperature-  
244 controlled water bath. After the gastric digestion, samples were immediately adjusted to pH 7 with 1 M NaOH.  
245 Digested samples were added to simulated intestinal solution and incubated at 37 °C for 2 H. Samples were  
246 adjusted to pH 9 to ensure enzyme inactivation.

247

### 248 **2.15. Hemolytic activity**

249 The hemolytic activity was determined according to the method of Pata et al. [27]. After isolation of the  
250 erythrocytes by centrifugation at 1,000g for 5 min, human red blood cells (hRBCs) were washed three times  
251 with PBS, pH 7.4 and then adjusted to 2% (v/v). Ten microliter CHHs were added separately to the 100 µL  
252 reaction solution, incubated for 1 H at 37 °C and centrifuged at 1,000g for 5 min. 100 µL of supernatant was  
253 then transferred into 96-well plate. The absorbance was measured at 415 nm. 1% (v/v) Triton X-100 and DI  
254 used as positive and negative control respectively. All samples were analyzed in quadruplicate.

255

### 256 **2.16. Statistical analysis**

257 Statistical analysis was performed using ANOVA and followed by Dunnett's test (Prism 5.0, GraphPad Inc., San  
258 Diego, CA, USA). Data are presented as mean ± SEM. A value of  $P < 0.05$  was accepted to be significant ( $*P <$   
259  $0.05$ ,  $**P < 0.01$ ,  $***P < 0.001$ ).

260

## 261 **3. Results and Discussion**

### 262 **3.1. Preparation of crocodile hemoglobin hydrolysates (CHHs) and degree of hydrolysis (DH)**

263 In the present study, crocodile (*C. siamensis*) hemoglobin was extracted from red blood cells. To obtain active  
264 fragments, crocodile hemoglobin was hydrolyzed by pepsin digestion at different reaction times. The extent of  
265 enzymatic protein degradation was evaluated by degree of hydrolysis (DH) which was 20.4%, 23.1%, 25.0%  
266 and 35.9% for 2 H, 4 H, 6 H and 8 H of incubation, respectively (Fig. 1). Results indicated that cleavage of  
267 peptide bonds was higher in longer enzymatic hydrolysis.

268

### 269 3.2. Antioxidant activity, purification and amino acid sequence identification of CHHs

270 NO is a very unstable radical which produces highly reactive molecules [28]. Intact crocodile Hb and all  
271 investigated Hb hydrolysates inhibited NO radicals (Fig. 2a). Notably, the hydrolysates had superior antioxidant  
272 activity compared to intact Hb at all concentrations (15-500  $\mu\text{g/mL}$ ). The NO-scavenging activity of the intact  
273 protein (500  $\mu\text{g/mL}$ ) was 75.7%, while the inhibitory ability of the hydrolysates, including 2H-CHH, 4H-CHH,  
274 6H-CHH and 8H-CHH, showed inhibition percentages of 77.4%, 78.2%, 88.3% and 83.1%, respectively.  
275 Moreover, BHT employed as positive standard displayed 77.8% NO radical inhibition. These results indicate  
276 that CHHs obtained by pepsin digestion possess pronounced antioxidant activity against nitric oxide radicals.  
277 From the report of Kabbua et al. [29] found that recombinant  $\alpha$ -globin from cHb can act as a heme-nitric oxide  
278 and/or oxygen binding (H-NOX) hemoprotein. Furthermore, the value of NO inhibition activity of CHH was  
279 higher than yellowfin tuna hydrolysate [30].

280 Lipid peroxidation is considered to be a free radical process involving a source of secondary free radical, which  
281 can act as secondary messenger or directly react with other biomolecules, enhancing biochemical lesions. The  
282 results of linoleic peroxidation assay reveal that 2H-CHH, 4H-CHH, 6H-CHH and 8H-CHH (at concentrations  
283 of 0.005-500  $\mu\text{g/mL}$ ) effected significant inhibition of linoleic peroxidation in a concentration dependent  
284 manner when compared with Trolox. The inhibitory ability of all hydrolysates, including 2H-CHH, 4H-CHH,  
285 6H-CHH and 8H-CHH were 94.2%, 79.0%, 97.0% and 82.2%, respectively. Moreover, Trolox (500  $\mu\text{g/mL}$ )  
286 showed 94.4% of linoleic peroxidation inhibition and intact Hb showed 89.1% inhibition (Fig. 2b). Furthermore,  
287 the linoleic peroxidation inhibition of protein hydrolysates obtained from smooth hound has been investigated.  
288 As shown by the results, the value of this activity was lower than that obtained in this study [31].

289 2H-CHH, 4H-CHh, 6H-CHH and 8H-CHH at the highest concentration (500  $\mu\text{g/mL}$ ) displayed significant ferric  
290 ion reducing power. 4H-CHH displayed the highest reduction activity equivalent to Trolox of about 2.1 mM,  
291 while intact Hb, 2H-CHH, 6H-CHH and 8H-CHH displayed reduction equivalents of 0.8, 1.2, 1.4 and 0.6 mM  
292 Trolox (Fig. 2c). Moreover, 500  $\mu\text{g/mL}$  glutathione (positive control) affected significant ferric ion reduction  
293 equivalent to Trolox at 18.60 mM (data not shown). It has been reported that hydrolysates with high reducing  
294 power show a great ability to donate electrons to form stable compounds and thereby interrupt the free radical  
295 chain reactions and showing antioxidant activity [32].

296 Due to displaying the highest antioxidant activity in prior experiments, 6H-CHH was subjected to purification  
297 by reverse phase C-18 column semi-preparative HPLC to identify the contained active peptide components. As  
298 shown in Fig. 3a, 61 individual fractions were eluted. All elution peaks were normalized to a concentration of 78

299  $\mu\text{g/mL}$  and screened with respect to antioxidant activity by nitric oxide scavenging assay. After the activity  
300 screening, several active fragments including P2, P39, P40, P43, P45, P46 and P57 were associated with nitric  
301 oxide radical inhibition rates of 19.5%, 21.2%, 17.3%, 16.1%, 18.7%, 18.1% and 32.0%, respectively. The  
302 highest activity in inhibiting nitric oxide radicals was found for P57 (32.0%), while the positive control (BHT)  
303 showed 68.1% nitric oxide radical inhibition (Fig. 3b).

304 The primary structures of the purified antioxidant peptides were elucidated using LTQ orbitrap XL mass  
305 spectrometry (Fig. 4). Amino acid sequence of P57 was KIYFPHF (KF7) with molecular mass of 476.26 Da. As  
306 shown in Table 1, antioxidant peptide KF7 showed 42% hydrophobicity and a +1 net charge. Alignment of the  
307 amino acid sequences of the peptide fragments with cHb indicated the antioxidant peptides originated from the  
308  $\alpha$ -subunit, this observation is in excellent agreement with results of Srihongthong et al. [9], who reported that  
309 the  $\alpha$ -subunit of cHb exhibited higher antioxidant activity than the  $\beta$ -subunit. Peptide fractions from acid-  
310 digested cHb with a molecular mass of 180 to 3,000 Da are reported to exhibit antioxidant activity [33].  
311 Notably, mass spectrometric analysis further revealed an apparent correlation of peptide length with biological  
312 activity as antioxidant peptides were found to be smaller and shorter molecules. In a previous study, Peña-  
313 Ramos et al. [34] reported that the presence of particular amino acids including His, Tyr, Met, Lys, Trp and Pro  
314 correlates with increased antioxidant potency of most food-derived peptides. Likewise, the presence of Leu, Ile,  
315 His, Met, Tyr, Lys and Trp is assumed to contribute to the reducing power of protein hydrolysates [35]. In  
316 addition, peptides containing His residues have been documented to exhibit protective effects against lipid  
317 peroxidation. An imidazole ring of His has been implicated in the donation of hydrogen and trapping of lipid  
318 radicals [36]. Trp, Tyr and Met exhibited the highest antioxidant properties, followed by Phe, Cys and His [37].  
319 Nitric oxide, however, is also scavenged by CHH, presumably due to the presence of reactive thiol groups [38].

320

### 321 3.3. Anti-inflammatory activity, purification and amino acid sequences identification of CHHs

322 The anti-inflammatory property of intact Hb and CHHs was evaluated on the basis of NO production and cell  
323 viability against macrophage RAW 264.7 cells (Fig. 5). After induction of inflammation in RAW 264.7 cells by  
324 LPS for 24 H, the percentage of nitric oxide production was defined as 100% when treated with LPS. Fig. 5a,  
325 2H-CHH, 4H-CHH, 6H-CHH and 8H-CHH (at concentrations of 62-500  $\mu\text{g/mL}$ ) show nitric oxide production  
326 decrease in a concentration dependent manner. Intact Hb, 2H-CHH, 4H-CHH, 6H-CHH and 8H-CHH at a  
327 concentration of 500  $\mu\text{g/mL}$  show nitric oxide production at 56.5%, 52.6%, 68.6%, 62.0% and 60.9%,  
328 respectively. In order to evaluate potential cytotoxic effects of CHHs, the viability of RAW 264.7 cells treated

329 with defined concentrations of CHHs was determined (Fig. 5b). The results showed that intact Hb, 2H-CHH,  
330 4H-CHH, 6H-CHH and 8H-CHH at concentrations of 62-500  $\mu\text{g/mL}$  had no observable effect on cell viability  
331 while the viability percentage of cells treated with LPS only was defined as 100%. This result indicates that  
332 CHHs show high efficacy to reduce nitric oxide production and are essentially non-toxic to macrophage RAW  
333 264.7 cells, these results correlate with that from the report of Phosri et al. [11] who reported that cHb provides  
334 anti-inflammatory activity via the suppression of nitric oxide synthase (NOS), which inhibits the NO  
335 production. Jangpromma et al. [39] reported that cHb significantly decreased the production of NO in LPS-  
336 stimulated RAW 264.7 cells and decreased inducible nitric oxide synthase (iNOS). In addition, results showed  
337 that CHHs have higher anti-inflammatory activity than gastropod (*Harpa ventricosa*) hydrolysate [40].  
338 Since 2H-CHH was found to possess the highest anti-inflammatory activity, its peptide constituents were  
339 purified by reverse phase C-18 column semi-preparative HPLC. The resulting chromatogram depicted in Fig. 6a  
340 consists of 59 fraction peaks which were diluted to a concentration of 31  $\mu\text{g/mL}$  prior to anti-inflammatory  
341 activity determination. The assay revealed 6 peaks (P16, P17, P28, P29, P30 and P38) which show nitric oxide  
342 production at 83.2%, 86.0%, 87.9%, 88.8%, 86.3% and 83.6% (Fig. 6b) with no effect on the viability of RAW  
343 264.7 cells (Fig. 6c). Moreover, these fractions were also selected to determine the influence on the expression  
344 levels of IL-6, IL-1 $\beta$  and PGE<sub>2</sub> (Table 2). The results indicate that P16, P17, P28, P29, P30 and P38 are able to  
345 significantly decrease IL-6 and PGE<sub>2</sub> production, whereas P16 and P17 further inhibited IL-1 $\beta$  production.  
346 Notably, P16 showed the highest activity to decrease IL-6 levels (approximately 2.0 ng/mL) compared to LPS  
347 and effectively decreased the IL-1 $\beta$  level to about 0.3 ng/mL. P16 showed the highest activity to reduce PGE<sub>2</sub>  
348 levels (approximately 1.9 ng/mL) when compared to LPS. Furthermore, P16 was found to reduce the production  
349 of pro-inflammatory cytokines and inflammatory mediators IL-6, IL-1 $\beta$  and PGE<sub>2</sub>, which are associated with the  
350 inflammation-related in neuropathological diseases, for example Alzheimer's, multiple sclerosis and cerebral  
351 ischemia [41, 42]. IL-6 that acts as a multifunctional cytokine was up-regulated by lipopolysaccharide (LPS). In  
352 inflammation, trauma and autoimmune diseases were found high expression levels of IL-1 $\beta$  and IL-6 [43].  
353 Furthermore, IL-1 $\beta$  induced IL-6 production is mediated predominantly through the p38 MAPK/NF- $\kappa$ B  
354 pathway [44]. cHb was found to exhibit anti-inflammatory effects in the cotton pellet model and RAW 264.7  
355 cells by reducing expression levels of IL-1 $\beta$ , TNF- $\alpha$ , COX-2 and IL-6 mRNA [39, 45]. The collected results in  
356 this work indicate that the anti-inflammatory activity of sample might be related to an interaction with the  
357 MAPK/NF- $\kappa$ B pathway by their ability to decrease pro-inflammatory cytokine and inflammatory mediator  
358 production.

359 The primary structures of the purified anti-inflammatory peptides were elucidated using LTQ orbitrap XL mass  
360 spectrometry (Fig. 4). Amino acid sequences of P16 were determined as SAFNPHEKQ (SQ9) and  
361 IHNKVKVAHGKKVL (IL15) corresponding to molecular mass of 529.26 Da and 857.51 Da, respectively. As  
362 shown in Table 1, anti-inflammatory peptides SQ9 and IL15 had hydrophobicity values of about 22% and 40%,  
363 together with net charges of 0 and +2, respectively. The sequence of the anti-inflammatory peptide showed  
364 strong correlation with the  $\beta$ -chain of cHb. Likewise, the anti-inflammatory activity of SQ9 and IL15 was traced  
365 back to the presence of specific amino acids. According to reports, anti-inflammatory peptides can be found in a  
366 wide molecular weight range [20, 46]. Hydrophobic amino acid side chains (e.g. Leu, Phe, Val, Ile, and Trp) as  
367 well as positively charged amino acids (Lys, Arg and His) were documented to have a major influence on the  
368 anti-inflammatory activity of peptides [47-52].

369

### 370 3.4. *In vitro* simulated gastric and intestinal digestion of CHHs and its activity

371 Simulated gastric and intestinal digestion (*in vitro* digestion model) was used as the conditions of human  
372 stomach and intestine. The degree of hydrolysis of 2H-CHH and 6H-CHH after intestinal digestion was  
373 increased about 3.7% and 8.8%, respectively. From the results, it is inferred that CHH tended to be more  
374 hydrolyzed by intestinal digestion. Gastrointestinal tract is known to be a major oxidation site where various  
375 free radicals are generated in the digestion process [53]. As shown in Fig. 7a, 6H-CHH after intestinal digestion  
376 was inhibited nitric oxide (42.5%, the concentration of 125  $\mu\text{g}/\text{mL}$ ) and exhibited higher reducing power (2.8  
377 mM Trolox equivalent, the concentration of 500  $\mu\text{g}/\text{mL}$ ) than 6H-CHH before intestinal digestion (Fig. 7b).  
378 With excellent agreement with Moure et al. [36] who reported that the reducing power increased with higher  
379 degree of hydrolysis. The anti-inflammatory activity of 2H-CHH after intestinal digestion showed NO  
380 production (19.8%, the concentration of 125  $\mu\text{g}/\text{mL}$ ) without toxicity against macrophage RAW 264.7 cells  
381 (Figs. 8a and 8b). During the course of the inflammation high amounts of free radicals are produced within the  
382 inflamed tissue, in particular NO, which acts as a major pro-inflammatory mediator in the human body and is  
383 generated from macrophage in response to the inflammation [8]. In this context, NO is generally regarded as the  
384 key mediator correlating inflammation and oxidative stress. The capability of NO production has decreased  
385 resulting in the reduction of detrimental effects of both inflammation and oxidative damage. The hemolytic  
386 activity was performed to determine the toxicity against human red blood cells and the results showed that both  
387 2H-CHH and 6H-CHH at all concentrations were not toxic against human red blood cells (Figs. 9a and 9b). So  
388 far, only a few bioactive peptides including peptides in this study displaying activities *in vitro* that have been

389 proven effective *in vivo*. Results indicated that both 2H-CHH and 6H-CHH with intestinal digestion have  
390 potential to be used as an alternative source of antioxidant and anti-inflammatory agents with safety.

391

#### 392 **4. Conclusions**

393 A number of novel antioxidant and anti-inflammatory peptides were derived from pepsin hydrolysis of cHb.  
394 Experimental evidence collected in this study indicates the antioxidant fragment is a comparatively small  
395 peptide, consisting of only 7 amino acid residues with slightly positive charge and low hydrophobicity.  
396 Similarly, the peptides with anti-inflammatory activity were found to comprise 9 and 15 amino acid residues,  
397 respectively, and are also characterized by positive charge and low hydrophobicity. This is the first report to  
398 identify antioxidant and anti-inflammatory peptides from pepsin digested cHb. Due to their remarkable  
399 biological activity, ease of production and absence of cytotoxicity, these naturally-derived peptides are believed  
400 to bear a great potential for a future application as health promoting supplements and therapeutic agents against  
401 inflammation and oxidative stress-related conditions.

402

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411

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**TABLE 1** *Structural characteristics of the anti-inflammatory peptides (P16) from 2H-CHH and antioxidant peptide (P57) from 6H-CHH*

<i>Properties</i>	<i>Peptide sequences</i>	<i>Hydrolysates</i>	<i>% hydrophobicity</i>	<i>Net charge</i>	<i>Sequence alignment</i>
Anti-inflammatory	SAFNPHEKQ (SQ9)	2H-CHH	22%	0	cHb $\beta$ -subunit (position 2-10)
Anti-inflammatory	IIHNEKVQAHGKKVL (IL15)	2H-CHH	40%	+2	cHb $\beta$ -subunit (position 55-69)
Antioxidant	KIYFPHF (KF7)	6H-CHH	42%	+1	cHb $\alpha$ -subunit (position 41-47)

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**TABLE 2**

*IL-6, IL-1 $\beta$  and PGE<sub>2</sub> production in LPS-stimulated RAW 264.7 cells incubated with purified fractions of 2H-CHH at a concentration of 31  $\mu$ g/mL*

<i>Fraction peaks (P)</i>	<i>The production concentration (ng/mL)</i>		
	<i>IL-6</i>	<i>IL-1<math>\beta</math></i>	<i>PGE<sub>2</sub></i>
LPS	10.647 $\pm$ 0.213	0.360 $\pm$ 0.002	6.486 $\pm$ 0.163
P16	2.019*** $\pm$ 0.000	0.315*** $\pm$ 0.002	1.871*** $\pm$ 0.068
P17	7.287*** $\pm$ 0.447	0.338 $\pm$ 0.001	1.877*** $\pm$ 0.042
P28	7.967*** $\pm$ 0.110	0.420*** $\pm$ 0.002	3.046*** $\pm$ 0.220
P29	9.340* $\pm$ 0.155	0.412*** $\pm$ 0.001	3.578*** $\pm$ 0.035
P30	9.407* $\pm$ 0.116	0.430*** $\pm$ 0.002	2.880*** $\pm$ 0.205
P38	4.707*** $\pm$ 0.173	0.538*** $\pm$ 0.011	3.181*** $\pm$ 0.377

521

\*denotes  $P < 0.05$  and \*\*\* denotes  $P < 0.001$ . Data expressed as a mean  $\pm$  SEM of 3 independent experiments.

Significance was measured using ANOVA followed by Dunnett's test.

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529 **Figure captions**

530

531 **FIG. 1** Degree of hydrolysis (% DH) of CHH after pepsin digestion for 2, 4, 6 and 8 H. Hemoglobin  
 532 hydrolyzed enzymatically by pepsin displayed a direct correlation between the rate of hydrolysis (DH)  
 533 and the time of incubation (H).

534

535 **FIG. 2** (a) Nitric oxide scavenging activity of CHHs at concentrations of 15-500 µg/mL. Each bar displays the  
 536 mean ± SEM of four demonstrations. (\*\* P < 0.01 and \*\*\* P < 0.001) probability levels compared  
 537 with BHT. (b) Linoleic peroxidation activity of CHHs at concentration of 0.005-500 µg/mL. Each bar  
 538 displays the mean ± SEM of six demonstrations. (\* P < 0.05, \*\* P < 0.01 and \*\*\* P < 0.001)  
 539 probability levels compared with Trolox and (c) reducing power of CHHs at concentration of 0.005-  
 540 500 µg/mL expressed in Trolox equivalents. Each bar displays the mean ± SEM of four demonstrations.  
 541 (\*\*\*P < 0.001) probability levels compared with glutathione.

542

543 **FIG. 3** Reverse phase C-18 column semi-preparative HPLC profile of (a) 6H-CHH. 0.1% Trifluoroacetic acid  
 544 (TFA) in deionized water and 60% acetonitrile in 0.1% Trifluoroacetic acid (TFA) were chosen as  
 545 mobile phase A and B, respectively. CHH was filtered through 25 mm PES filters and 700 µg (4 mL)  
 546 were injected at 1.0 mL/min of flow rate. The linear gradient was 0-25% (v/v) mobile phase B over 15  
 547 min, then 25-100% (v/v) mobile phase B over 95 min. (b) The antioxidant activity of purified peaks  
 548 from 6H-CHH (78 µg/mL) determined by the nitric oxide scavenging assay. Each bar displays the  
 549 mean ± SEM of four demonstrations (\*\*\* P < 0.001).

550

551 **FIG. 4** Mass spectrogram of anti-inflammatory peptides and antioxidant peptide from P16 (2H-CHH) and P57  
 552 (6H-CHH), respectively, determined by LTQ orbitrap XL mass spectrometry. The following sequence  
 553 interpretation was concluded: anti-inflammatory peptides were identified as (a) Ser-Ala-Phe-Asn-Pro-  
 554 His-Glu-Lys-Gln (SAFNPHEKQ) and (b) Ile-Ile-His-Asn-Glu-Lys-Val-Gln-Ala-His-Gly-Lys-Lys-Val-  
 555 Leu (IIHNEKVQAHGKKVL) and (c) the antioxidant peptide was identified as Lys-Ile-Tyr-Phe-Pro-  
 556 His-Phe (KIYFPHF).

557

558 **FIG. 5** *The effect of CHHs on (a) NO production in LPS-activated macrophage RAW 264.7 cells and (b) the*  
559 *cytotoxicity (cell viability) of CHHs on macrophage RAW 264.7 cells determined by the MTT assay.*  
560 *CHHs (62-500 µg/mL) were then incubated with macrophage RAW 264.7 cells and another overnight*  
561 *incubation was set between LPS and macrophage RAW 264.7 cells. The media were further used to*  
562 *measure the nitrite level (NO assay). Each bar displays the mean ± SEM of four demonstrations (\* P <*  
563 *0.05, \*\* P < 0.01 and \*\*\* P < 0.001).*

564  
565 **FIG. 6** *Reverse phase C-18 column semi-preparative HPLC profile of (a) 2H-CHH. 0.1% Trifluoroacetic acid*  
566 *(TFA) in deionized water and 60% acetonitrile in 0.1% Trifluoroacetic acid (TFA) were chosen as*  
567 *mobile phase A and B, respectively. CHH was filtered through 25 mm PES filters and 700 µg (4 mL)*  
568 *were injected at 1.0 mL/min of flow rate. The linear gradient was 0-25% (v/v) mobile phase B over 15*  
569 *min, then 25-100% (v/v) mobile phase B over 95 min. (b) The anti-inflammatory property of purified*  
570 *peaks from 2H-CHH (31 µg/mL) against NO production determined in LPS-activated macrophage*  
571 *RAW 264.7 cells. (c) The cytotoxicity (cell viability) of purified peaks from 2H-CHH (31 µg/mL) on*  
572 *macrophage RAW 264.7 cells determined by the MTT assay. Each bar displays the mean ± SEM of four*  
573 *demonstrations (\* P < 0.05, \*\* P < 0.01 and \*\*\* P < 0.001).*

574  
575 **FIG. 7** *(a) Nitric oxide scavenging activity of 6H-CHHs after intestinal digestion at concentrations of 15-125*  
576 *µg/mL. Each bar displays the mean ± SEM of four demonstrations. (\* P < 0.05 and \*\*\* P < 0.001)*  
577 *probability levels compared with BHT. (b) Reducing power at concentration of 0.005-500 µg/mL*  
578 *expressed in Trolox equivalents. Each bar displays the mean ± SEM of four demonstrations. (\*\*\*)*  
579 *0.001) probability levels compared with glutathione.*

580  
581 **FIG. 8** *The effect of 2H-CHHs after intestinal digestion on (a) NO production in LPS-activated macrophage*  
582 *RAW 264.7 cells and (b) the cytotoxicity (cell viability) on macrophage RAW 264.7 cells determined by*  
583 *the MTT assay. 2H-CHHs (31-125 µg/mL) were then incubated with macrophage RAW 264.7 cells and*  
584 *another overnight incubation was set between LPS and macrophage RAW 264.7 cells. The media were*  
585 *further used to measure the nitrite level (NO assay). Each bar displays the mean ± SEM of four*  
586 *demonstrations (\* P < 0.05, \*\* P < 0.01 and \*\*\* P < 0.001).*

587

588 **FIG. 9** *The hemolytic activity of (a) 2H-CHH after intestinal digestion and (b) 6H-CHH after intestinal*  
589 *digestion against human red blood cells. Each bar displays the mean  $\pm$  SEM of four demonstrations*  
590 *(\*\*\*  $P < 0.001$ ).*

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