

1 **Which casein in sodium caseinate is most resistant to *in vitro* digestion? Effect of**
2 **emulsification and enzymatic structuring**

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17
18 **Abstract**

19 We investigated the resistance of individual constituent casein epitopes (α S₁-, α S₂-, β - and κ -CN)
20 in food-grade milk protein sodium caseinate (NaCN) to simulated human gastro-duodenal digestion.
21 The influence of NaCN adsorption to the surface of oil-in-water emulsion droplets and the effect of
22 crosslinking of the protein with enzyme transglutaminase (TG) on the proteolysis were studied by
23 indirect ELISA. TG crosslinking rendered fragments of casein molecules significantly resistant to
24 digestion. However, it depended on the type of casein and whether NaCN was presented in solution
25 or emulsion. The crosslinking was found to considerably hinder the digestion of several amino acid
26 regions in one of the major caseins of NaCN, β -CN. For α S₁- and α S₂-CN, only limited resistance to
27 digestive enzymes was observed after NaCN had been crosslinked in solution but not (or to a limited
28 extent) in emulsion. κ -CN proved to be the least resistant to the enzymatic hydrolysis regardless of
29 the TG treatment. Our work shows for the first time how the digestibility of individual components of
30 important food-grade protein ingredients can differ in a complex, colloidal food system. It also shows
31 an example of how the digestibility can be modulated by chemical and physical structuring.

32
33 **Keywords:** Digestion; Sodium caseinate; ELISA; Emulsion; Transglutaminase; Casein

34
35 **1. Introduction**

36 Micro- and macro-structural organisations of proteins in foods are often generated by various food
37 processing methods (e.g., emulsification, heating, gelation, enzymatic treatment, etc.). Although
38 required to create desirable, functional structures in food, the processing can render proteins either
39 significantly less or significantly more accessible for the digestive enzymes of the human

40 gastrointestinal tract and hence modify amino acid bioaccessibility during digestion (Singh & Ye, 2013;
41 Gan, Bornhorst, Henrick, & German, 2018).

42 The digestion of a single protein leads to the release of hundreds of peptides in the gut lumen that
43 can be identified by mass spectrometry (Boutrou et al., 2013) but the information is only semi-
44 quantitative. It is therefore difficult to get a clear picture of the extent of hydrolysis of a specific protein
45 domain (Dupont, 2017). An alternative to the mass spectrometry has been proposed based on the use
46 of monoclonal antibodies with known specificity (Dupont, Rolet-Repecaud, & Senocq, 2003). The
47 underlying idea is that when an antibody binds the epitope of a protein that contains a protease
48 cleavage site, it means that the epitope has not been cleaved by the enzyme. In contrast, hydrolysis
49 of the epitope causes a loss of interaction between the antibody and the target protein that can be
50 easily monitored by immunoassays such as ELISA. This strategy was successfully applied to follow
51 proteolysis events occurring during cheese ripening (Senocq, Dupont, Rolet-Repecaud, & Levieux,
52 2002). As a result of their loose structure, caseins (CNs) are particularly adapted to this approach as
53 most of their epitopes are sequential, allowing the production of a wide collection of monoclonal and
54 polyclonal antibodies targeting several epitopes of αS_1 -, αS_2 -, β - and κ -CN (Johansson et al., 2009).

55 Enzymatic crosslinking of proteins is an attractive and feasible food technology due to the specificity
56 of enzymes and the mild reaction conditions (Buchert et al., 2010). Modification with crosslinking
57 enzymes such as transglutaminase (TG) has been extensively used to change the functionality of
58 proteins and thereby to improve the textural quality, stability and function of protein-based food
59 products (Dickinson, 1997). The enzyme permanently crosslinks proteins through an acyl transfer
60 mechanism between glutamine and lysine residues (Griffin, Casadio, & Bergamini, 2002). Monogioudi
61 et al. (Monogioudi et al., 2011) showed that enzymatically crosslinked purified β -CN was more
62 resistant to pepsin than a non-crosslinked protein. The crosslinking was also shown to delay the
63 simulated human gastro-duodenal proteolysis of food-grade protein sodium caseinate (NaCN) in
64 emulsion, which prevented the emulsion from destabilising under the gastric conditions (Macierzanka
65 et al., 2012). Our recent *in vivo* human study (Juvonen et al., 2015) showed that even subtle structural
66 modification of NaCN interfacial layer in emulsion by TG was able to alter the early postprandial profiles
67 of glucose, insulin, CCK, appetite and satiety through a decreased protein digestion, without
68 significantly affecting the gastric emptying or an overall lipid digestion. Although we showed significant
69 differences in the extent of digestion between NaCN crosslinked in emulsion and in solution
70 (Macierzanka et al., 2012), the detailed roles of constituent casein epitopes of NaCN (i.e., αS_1 -, αS_2 -,
71 β - and κ -CN) in exerting the resistance to digestion could not be evaluated. This fundamental
72 knowledge is required for developing novel foods as the nutritional interventions aiming to modulate
3 dietary protein bioaccessibility and amino acid bioavailability provides the best strategy for preventing
4 diet-related health problems such as food allergies or sarcopenia.

6 2. Materials and methods

7 2.1. Materials

78 Food-grade sodium caseinate (NaCN; 90% protein) was obtained from DMV International (The
79 Netherlands). Microbial transglutaminase (TG) and triglyceride oil were treated as described before
80 (Macierzanka et al., 2012). Details have also been given in the Supplementary Material (SM; S1.1.).
81 Eighteen monoclonal antibodies and one polyclonal antibody (SM; Table S1, Fig. S1) were taken from
82 the INRA's collection in order to cover as much of the sequences of αS_1 -, αS_2 -, β - and κ -CN as possible
83 (Johansson et al., 2009; Fig. S1). More details have been given in the SM (S1.1.).

84 **2.2. NaCN in emulsion and solution; sample preparation and characterisation**

85 The preparation of NaCN-stabilised emulsions and NaCN solutions, TG crosslinking, *in vitro* gastro-
86 duodenal digestion experiments, and SDS-PAGE characterisation of the digestion samples were done
87 as described previously (Macierzanka et al., 2012). For convenience, detailed experimental
88 procedures have also been given in the SM.

89 **2.3. Indirect ELISA**

90 The indirect ELISA was performed for selected time-point samples from digestion of NaCN in order
91 to detect protein regions (in αS_1 -, αS_2 -, β - and κ -CN) resistant to digestion, using the antibodies listed
92 in Table S1. Detailed experimental procedure has been described in the SM (S1.7.)

94 **3. Results and discussion**

95 **3.1. SDS-PAGE characterisation**

96 We have investigated the impact of NaCN adsorption to the oil-water interface in an emulsion and
97 its subsequent crosslinking with TG on the susceptibility of constituent casein polypeptides to
98 simulated human gastro-duodenal proteolysis. SDS-PAGE was used initially to provide a rapid
99 screening of the overall behaviour of NaCN during the digestion experiments carried out for the protein
100 presented in different physical-chemical states (i.e., in solution vs. adsorbed, and non-crosslinked vs.
101 covalently crosslinked by TG) and under different conditions (i.e., +/- vesicular PC in the gastric
102 digestion compartment). This initial part of the study was carried out using a similar approach to the
103 work presented previously (Macierzanka et al., 2012). Therefore, it was important to demonstrate that
104 the SDS-PAGE characterisations of the digestion products in the present study were consistent with
105 the results shown in that report. This offers a coherent experimental introduction to the original ELISA
106 results reported in this paper. The SDS-PAGE results are shown in the Supplementary Material (SM;
107 Fig. S2). Because of their consistency with the previously published work (Macierzanka et al., 2012),
108 detailed description and discussion of the results have only been given in the SM (S2.1.).

110 **3.2. ELISA study**

1 An important consideration before analysing ELISA results is an effect that crosslinking might have
2 on the binding properties of antibodies, i.e., whether the crosslinking could block antibodies even
3 though the peptides they are specific to remain intact during the digestion. Crosslinking could
4 theoretically affect antibody binding the target protein, causing a decrease in immunoreactivity due to
5 steric hindrance. Nevertheless, in the present study, ELISA results were expressed as residual
6 immunoreactivity (RI) normalised against the immunoreactivity detected for undigested protein (native

117 i.e. non-crosslinked, or crosslinked), thereby accounting for potential changes in antibody binding
118 efficiency resulting from crosslinking. A loss of signal, therefore, means a hydrolysis of the epitope and
119 not steric hindrance.

120 After crosslinking NaCN with TG, significant RIs of several β -CN fragments were observed in
121 digestion samples (Fig. 1). This suggests that the crosslinking restricted hydrolysis by digestive
122 enzymes. The RI was significantly lower for the non-crosslinked protein. The fragment f4-28 was the
123 only one, for which the RI of over 80% persisted until the end of the gastric phase and was still up to
124 ca. 60% during the first 5 min of the duodenal proteolysis (Fig. 1B,D). In emulsion, approximately 70%
125 of the adsorbed β -CN is closely associated with the oil-water interface (Mackie, Mingins, & North,
126 1991), with one exception being the sequence of 40–50 residues at the N-terminus. The sequence is
127 predominantly hydrophilic and thus oriented into the aqueous phase (Dickinson, 2006). It contains four
128 phosphoserine residues (Table S1). The electrostatic repulsion produced by this part of the protein is
129 crucial for preventing coalescence of emulsion droplets (Caessens, Gruppen, Slangen, Visser, &
130 Voragen, 1999). All the above suggests that the fragment f4-28 might remain exposed to the TG, not
131 only in solution but also after the protein had been adsorbed to oil droplets in emulsion. This fragment
132 contains one lysine (Table S1) that is the likely residue crosslinked and responsible for the high RI
133 observed during the gastric phase of digestion (Fig. 1B,D). In the absence of crosslinking, the fragment
134 was much more susceptible to pepsinolysis, and the RI fell to ca. 10% after 60 min of gastric digestion
135 (Fig. 1A,C).

136 Another segment of β -CN, which expressed increased resistance to pepsin after crosslinking was
137 the fragment f94-113 (Fig. 1F,H). At the end of the gastric digestion, its RI was up to ca. 40%
138 depending on the crosslinking and digestion conditions (i.e., solution vs. emulsion, +/- PC). This short
139 region of β -CN contains five lysine residues (Table S1) that could be crosslinked, and hence restrict
140 access of pepsin during the digestion. However, in the absence of PC, relatively high RI (up to ca.
141 30% under the gastric conditions) of this fragment was also seen for the non-crosslinked protein
142 digested in emulsion (Fig. 1G). This suggests that adsorption to the interface alone might have
143 contributed to restricting access of pepsin. Much higher resistance to pepsinolysis (RI of ca. 95% in
144 the absence of PC) was recorded for the adjacent fragment f133-150, regardless of the TG pre-
145 treatment in emulsion (Fig. 1K,L), but not in solution (Fig. 1 I,J), indicating protection must have been
146 limited to the protein segment adsorbed at the oil–water interface. Both, f133-150 and f94-113 are
147 parts of the M_r 6 kDa peptide, which can persist during the pepsinolysis of purified β -CN in emulsion
148 (Macierzanka et al., 2009). The f133-150 contains several aliphatic residues and a tryptophan (Table
149 S1), which may be closely associated with the oil phase (Dickinson, Horne, Pinfield, & Leermakers,
0 1997). Such a close interaction of the M_r 6 kDa peptide with the oil phase was suggested to be the
1 reason for its protection from pepsinolysis (Macierzanka et al., 2009). Here, such behaviour has been
2 confirmed by ELISA for β -CN adsorbed to the interface in the presence of several other constituent
3 caseins of a food-grade NaCN. In the presence of PC, the protective effect of the interface was
4 completely abolished for the f133-150 (Fig. 1K,L) and significantly reduced for the f94-114 (Fig. 1G),

155 so their resistance to digestion was similar to that observed in solution (Fig. 1I,J and 1E, respectively).
156 Vesicular PC introduced to the gastric digestion mix is very efficient in displacing protein (including
157 NaCN) from the oil–water interface into the surrounding aqueous phase of emulsion as the lipid is
158 more surface active (Macierzanka et al., 2009; Macierzanka et al., 2012) After rapid desorption, the
159 protein is then digested with the kinetics similar to those observed in solution. Here, it has been clearly
160 seen for both f133-150 and f94-113.

161 The crosslinking also improved the RI of f167-178 (Fig. 1N), although to a lesser extent in emulsion
162 (Fig. 1P). This short protein fragment contains two lysine and two glutamine residues (Table S1), which
163 could have been crosslinked and therefore contributed to restricting the hydrolysis. Other fragments
164 of β -CN (i.e., f33-49 and f184-202) showed very little RI (SM; Fig. S3).

165 We have observed a rapid degradation of α S₁-CN in non-crosslinked NaCN (Figs. 2, S4). The TG
166 crosslinking improved resistance of two protein fragments (i.e., f56-74 and f75-92) to hydrolysis by
167 pepsin, however the protection was predominantly observed for the protein crosslinked in solution
168 (Fig. 2B,F) than in emulsion (Fig. 2D,H). The adsorbed α S₁-CN molecule is depicted as a tri-block
169 polymer, with a hydrophobic region at each end and a hydrophilic central loop containing several
170 phosphoserines (Dickinson, 2006). Thus, one can expect that in both emulsion and solution the TG
171 should have accessed and crosslinked the central region of the protein more easily than the terminal
172 regions. Interfacial rheology studies (Faergemand, Murray, Dickinson, & Qvist, 1999) demonstrated
173 that the structural build-up for adsorbed α S₁-CN was slower than for either β -CN or NaCN. This was
174 assumed to be caused by slower adsorption of α S₁-CN and/or possibly faster crosslinking of the other
175 proteins. A significant decrease in crosslinking kinetics (calculated from the loss of monomeric caseins
176 during the incubation with TG) upon protein adsorption to lipid droplet was found to be a general
177 phenomenon for all constituent caseins of NaCN (Macierzanka et al., 2011). However, crosslinking of
178 α S₁-CN was reduced much more significantly than other caseins. Hence, the limited crosslinking of
179 adsorbed α S₁-CN might have accounted for the low RI of f56-74 and f75-92 observed here (Fig. 2D,H).

180 Increased RI has been recorded for another fragment of α S₁-CN, f133-151, although similar results
181 were observed for both non-crosslinked and crosslinked samples, and only after the protein had been
182 adsorbed at the oil–water interface (Fig. 2K,L). This segment of α S₁-CN contains 7 hydrophobic
183 residues (i.e., Val, Ile, Met, 2× Phe, 2× Met), and was previously shown to reside very close to the
184 interface after protein adsorption (Dickinson et al., 1997). This close interaction with the oil might have
185 offered protection from proteolysis in a similar way as for fragments f133-150 and f94-113 of β -CN
186 (Fig. 1G,H,K,L), although, to a more limited extent. As with the β -CN fragments, the protection was
187 reduced when the digestion was carried out in the presence of PC (Fig. 2K,L), suggesting that also in
8 this case PC might have displaced the protein from the oil-water interface, so the protein was digested
9 mainly in the aqueous phase of emulsion. Other fragments of α S₁-CN (i.e., f1-19, f19-37, Nat f125-
0 132 and f149-166) showed very little RI (SM; Fig. S4).

1 We have also investigated the digestibility of the two minor constituents of NaCN: α S₂-CN and κ -
2 CN. For the digested emulsion samples, all of the α S₂-CN-specific antibodies returned very low RI,



193 regardless of the pre-treatment with TG (data not shown). α S₂-CN is the most hydrophilic of all caseins,
194 which is the result of three clusters of anionic groups in the amino acid sequence, composed of
195 phosphoserine and glutamyl residues (Farrell et al., 2004). The overall hydrophilic nature of α S₂-CN
196 could make it more exposed to the aqueous phase of emulsion than β -CN and α S₁-CN after NaCN
197 had been adsorbed to the oil droplets, therefore making α S₂-CN more vulnerable to the digestive
198 enzymes. This, coupled with its lower crosslinking rate in emulsion than in solution (Macierzanka et
199 al., 2011), would possibly explain that the limited resistance of the protein to digestion was only seen
200 after the crosslinking in solution (Fig. S5). The most pronounced effect was observed for f96-114 (Fig.
201 S5 F). This region of α S₂-CN contains one lysine and three glutamine residues (Table S1) that offer
202 potential sites for TG. However, it remains unclear why the other two epitopes (f16-35 and f76-95)
203 showed more modest resistance to digestion after the incubation with TG (Fig. S5 B,D) despite the
204 fact that they contain 5-6 TG amino acid substrates each (Table S1).

205 The antibodies specific to κ -CN only showed insignificant RI of this protein in NaCN samples
206 digested in solution or in emulsion (data not shown). The κ -CN contains lowest proportion of lysine
207 and glutamine residues, and less phosphoserine than other caseins (Farrell et al., 2004). It also
208 comprises a considerable amount of β -structure (Huppertz, Fox, & Kelly, 2018). Both of these factors
209 have been used to explain much poorer crosslinking of κ -CN compared to the other caseins in NaCN
210 (Macierzanka et al., 2011). In general, caseins in NaCN solutions exist as a dynamic system of casein
211 monomers, complexes, and aggregates (Lucey, Srinivasan, Singh, & Munro, 2000), depending on
212 conditions such as protein concentration, pH, ionic strength, temperature, etc. For example, at low
213 ionic strength (3 mM) NaCN was found to be present as individual molecules (HadjSadok, Pitkowski,
214 Nicolai, Benyahia, & Moulai-Mostefa, 2008) but formed small aggregates (hydrodynamic radius = 11
215 nm) at high ionic strength (>100 mM). In dilute aqueous solutions at neutral pH, NaCN consists
216 predominantly of protein nanoparticles (up to 20 nm) in equilibrium with free casein molecules, and
217 some supramolecular species composed largely of κ -CN (Dickinson, 2010). Recent discussion on
218 NaCN suspensions and casein micelles (Huppertz et al., 2017) proposed a model where NaCN
219 particle suspension consist of assembled non-spherical primary casein particles (PCPs, which are
220 naturally present in casein micelles). The κ -CN rich domains are likely to be located on the surface of
221 the assembled structures. The above characteristics may reflect conditions of the NaCN solutions
222 used in our present study. The possible easy access of digestive enzymes to κ -CN together with its
223 poor ability to crosslinking may therefore account for the rapid hydrolysis of the protein under the *in*
224 *vitro* digestion conditions.

225 For the α S₁-CN and the α S₂-CN, the crosslinking seemed to offer more protection to digestion after
6 the incubation of NaCN with TG in solution than in emulsion (Figs 2 and S5). Apart from the
7 aforementioned higher rate/degree of crosslinking of the caseins in solution (Macierzanka et al., 2011),
8 the reason might also lie in the type of the crosslinking observed in the two systems. In the same
9 studies, it was shown that incubation of NaCN with TG in solution might have led to some
0 intramolecular crosslinking as the oligomers formed were found to be more mobile on SDS-PAGE than
1 their counterparts formed from NaCN crosslinked at the oil-water interface, indicating that



232 intermolecular crosslinking might have prevailed at the interface. Therefore, the higher extent of
233 crosslinking and more compact structuring of the proteins offered by the intramolecular crosslinks
234 might account for some fragments of αS_1 -CN and αS_2 -CN incubated with TG in solution being more
235 resistant to digestion than those crosslinked in emulsion. This leads to the conclusion that the group
236 of oligomers of M_r ca. 50-100 kDa formed during the gastric digestion of crosslinked NaCN in emulsion
237 (Fig. S2 F), might have been mainly composed of the β -CN fragments that showed significant
238 resistance to pepsinolysis (Fig. 1).

239 Our results suggest that the TG crosslinking can improve resistance of casein molecules to
240 gastrointestinal digestion, if, for example, this is required for modulating phase behaviour of protein-
241 stabilised emulsions in the stomach and the rate of nutrients release (van Aken et al., 2011). The
242 findings might then be useful for optimising protein structuring in personalised nutrition in order to
243 modulate specific physiological responses to food, such as the ileal brake, which could in turn
244 determine satiety and calorie intake.

245

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251

252 Supplementary Material

253 Detailed description of the materials and methods used as well as additional data and discussion
254 of the results obtained.

255

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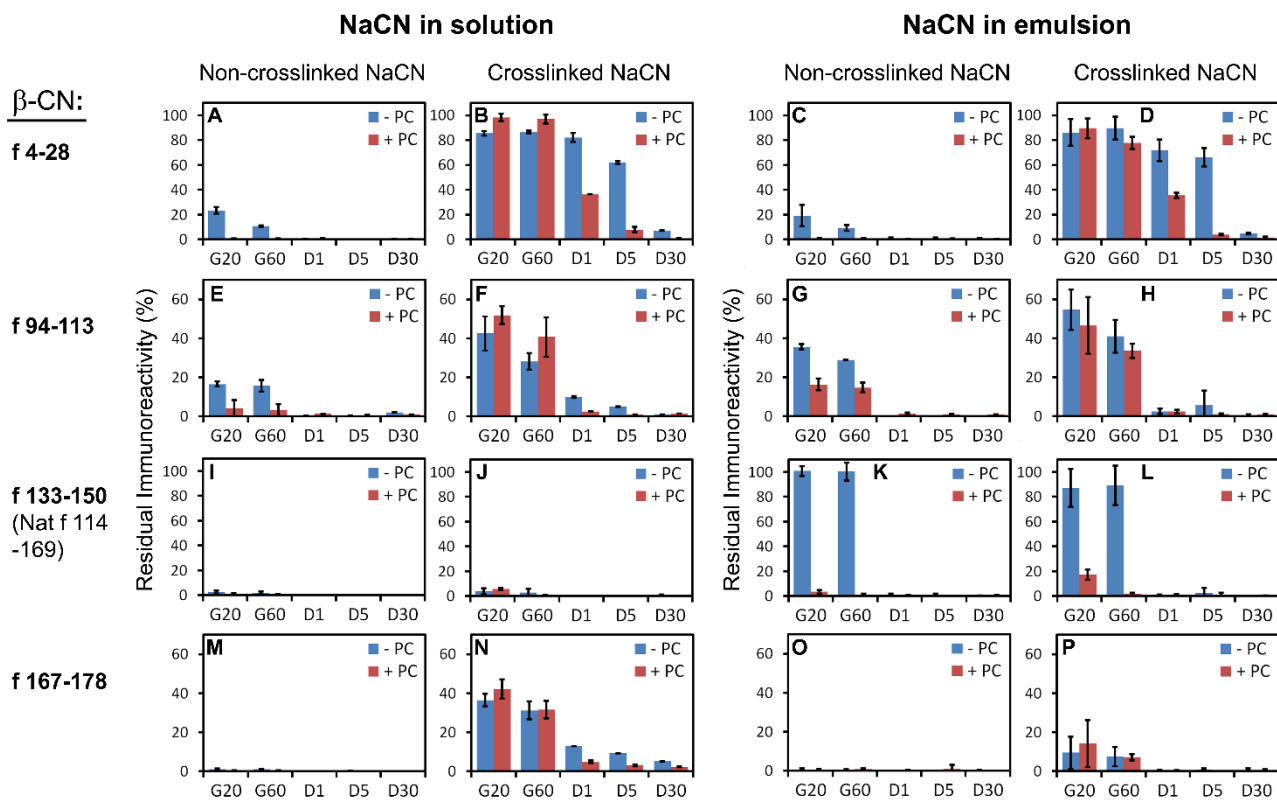
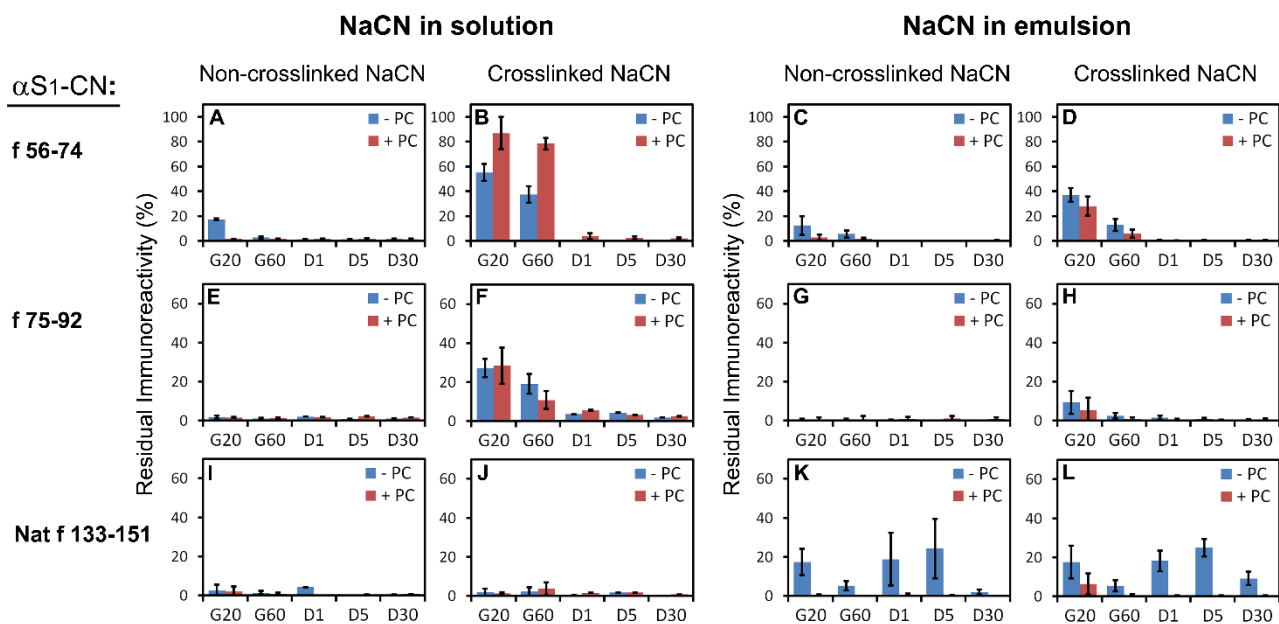


Fig. 1. Residual immunoreactivity (RI) of β -CN fragments (f) determined in time-point samples collected during the *in vitro* digestion of NaCN (results were normalised against the immunoreactivity detected for undigested protein sample; native i.e. non-crosslinked, or crosslinked). Effect of (i) presenting NaCN in aqueous solution (1 mg/mL) or emulsion (1 mg/mL), (ii) crosslinking of the protein with TG before digestion, and (iii) carrying out the digestion experiments in the presence or absence of vesicular phosphatidylcholine (PC) in the gastric phase of digestion. Gastric samples have been marked with G and duodenal with D, followed by a number corresponding to the digestion time (min) after which the samples were taken. Extended version of Fig. 1 has been shown in the Supplementary Material (Fig. S3).

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Fig. 2. Residual immunoreactivity (RI) of α S₁-CN fragments (f) determined in time-point samples collected during the *in vitro* digestion of NaCN. For more details see caption of Fig. 1. Extended version of Fig. 2 has been shown in the Supplementary Material (Fig. S4).

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