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Postnatal changes in the growth dynamics of the human face revealed from the bone modelling patterns

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Abbreviated title: Postnatal bone modeling in the human face

Key Words: *Homo sapiens*; facial skeleton; mandible; ontogeny; morphology; bone histology; modeling pattern; bone formation and resorption.

27 INTRODUCTION

28 The skull is an anatomically complex system, which has been a focal point for studies
29 in vertebrate biology for more than a century. It presents unique opportunities to examine the
30 role of the multiple, intricate developmental processes involved in the craniofacial
31 morphology and in the evolutionary origin of the hominid cranium. Understanding the
32 development of the skull can be achieved through the study of the growth dynamics of their
33 skeletal elements considering the Moss' functional matrices theory (Moss and Young 1960;
34 Moss 1962; Moss, 1970 c, d; Moss and Salentjin, 1969) and the Enlow's counterpart principle
35 (Enlow et al 1969; Enlow and Hans, 1996). According to this theoretical framework, the
36 human craniofacial skeleton results from the interactions of their different components that
37 are influenced by both internal (e.g. hormonal and genetic factors; e.g. Enlow and Hans, 1996;
38 Moss, 1960) and external stimuli (soft tissue growth, dental maturation, biomechanical
39 factors; e.g. Moss and Young, 1960; 1997a,b,c,d; Moss and Young, 1960; Moss and Rankow,
40 1968; Atchley and Hall, 1991; Enlow and Hans, 1996; Lieberman et al.,2002; Klingenberg et
41 al., 2003). The growth of the skeletal elements involves changes in their size and shape as
42 well as their relative position within the craniofacial system in order to maintain the proper
43 bone alignment, function and proportionate growth (e.g. O'Higgins et al., 1991; Enlow and
44 Hans, 1996; McCollum, 1999). During the human development, these skeletal elements from
45 the neurocranium, viscerocranium and mandible are intimately associated to the functional
46 spaces (cranial, orbital, nasal, and oral cavities) and the soft tissues in which they are
47 embedded (e.g. brain, muscles, connective tissues) (Moss and Young 1960; Moss, 1962;
48 1997a; Enlow and Hans, 1996).

49 The skull grows through two simultaneous and interrelated processes: growth
50 modelling and growth displacements of the skeletal elements. Growth modelling consists in
51 the coordinated activity of two cellular groups, osteoblasts forming bone on one surface and

52 osteoclasts removing bone in the opposite surface (Enlow, 1962; Bloom and Fawcett, 1994;
53 Enlow and Hans, 1996). This mechanism results in the increase in size of the bone and the
54 growth movement in the direction of the forming bone surfaces also termed cortical drift
55 (Enlow, 1962; 1963; Enlow and Harris, 1964). As a consequence of the bone modelling
56 growth, the skeletal components are displaced into the craniofacial system with coordinated
57 and passive movements -the primary and secondary displacements- as well as rotations (for a
58 detailed description of these movements see Björk, 1969; Moss and Young, 1960; Moss,
59 1970; Bjork and Skieller, 1972; 1976; Enlow and Hans, 1996).

60 In the last century, Enlow showed that the activity of osteoblasts and osteoclasts is
61 recorded in the bone surface (last formed bony lamellae) as fields of growth activity, bone
62 formation and resorption fields (Enlow, 1963; Enlow and Hans, 1996). The distribution of
63 these growth fields –the bone modeling pattern– is species-specific and its interpretation
64 following the craniofacial biology principles provide data on the growth dynamics of the
65 craniofacial skeletal components during human ontogeny (e.g. Enlow and Harris, 1964;
66 Mauser et al., 1975; Kurihara et al., 1980; Enlow and Hans, 1996; McCollum, 2008).
67 According to these studies, the prenatal craniofacial system shows a general growth as
68 indicated by the bone deposition surfaces (Mauser et al., 1975; Enlow and Hans, 1996;
69 Radlanski and Klarkowski, 2001). Bone resorption activity is first reported in the mandibular
70 corpus and ramus around 8,5th-9th prenatal weeks (Radlanski and Klarkowski, 2001; Mauser
71 et al., 1975; Enlow and Hans, 1996) indicating a lateral growth of the mandibular corpus and
72 a posterior relocation of the ramus (Mauser et al., 1975; Enlow and Hans, 1996). In the
73 postnatal period, the human facial skeleton is depository until 3 months of age, when bone
74 resorption surfaces appear in the nasoalveolar clivus (Kurihara *et al.*, 1980; Enlow and Hans,
75 1996; McCollum, 2008). From 2 to 14 years old, resorbing activity spread out over the
76 nasomaxillary region although the extension and the location of resorbing fields change

77 throughout ontogeny indicating changes in the growth dynamics associated to downward
78 growth of the human face (Kurihara et al., 1980; McCollum, 2008). Postnatal changes in the
79 bone modeling activity are also observed in the human mandible (Enlow and Harris, 1964;
80 Kurihara et al., 1980; Hans et al., 1995). At 2 years old, bone resorption fields appear for the
81 first time in the alveolar region of the buccal symphyseal region. From this age to 14 years
82 old, resorption extends towards the basal area of the symphyseal region and/or through the
83 anterior area of the mandibular corpus (Kurihara et al., 1980). During this postnatal period,
84 the mandibular ramus shows a complex modelling pattern indicating a posterior growth of the
85 mandible and its anterior displacement (Enlow and Harris, 1996). These studies analysed
86 facial skeleton growth up to 14 years old but the bone modelling activities during the
87 adulthood period remains almost unstudied. The aging craniofacial skeleton and mandible
88 show morphological changes related to their horizontally increase in size of the maxilla and
89 the mandible and to their increase in height of the anterior face (e.g. Behrents, 1985; Forsberg
90 et al., 1991; Bishara et al., 1994; Enlow and Hans, 1996; Bondevik, 1995; Doual et al., 1997;
91 West and McNamara, 1999; Akgül and Toygar, 2002; Albert et al. 2007; Williams and Slice,
92 2010; Tsiopas et al., 2011). In the present study, we analyse the postnatal growth dynamics of
93 the craniofacial skeleton comparing juvenile and adult specimens. We observe that adult and
94 juvenile specimens show different bone modelling patterns, adults presenting an increase of
95 bone formation surfaces in the maxilla and mandible that explains the horizontal and vertical
96 changes observed in aging craniofacial skeleton.

97 In addition, we explore how modelling activities of the facial skeleton and mandible
98 regions are related during the ontogeny. As mentioned above, the skeletal components
99 growing within the craniofacial complex system interact with each other keeping a functional
100 and structural balance whereas they increase in size during development (Enlow and Hans,
101 1996; Moss and Young, 1960; Moss, 1962). Correspondences between different anatomical

102 parts of the skull have been demonstrated by morphometric analyses (see Bastir *et al.*, 2006).
103 However, previous studies on the craniofacial growth through the analysis of modelling
104 activities have focused on particular facial or mandibular regions, except for Enlow's
105 reference work on craniofacial morphology in individuals up to 14 years old (Enlow, 1982,
106 revised in Enlow and Hans, 1996). In the present study, we hypothesize that ontogenetical
107 changes of the bone modelling also reflect the relationships between the facial and mandible
108 skeleton to maintain the functional and physiological balance of the craniofacial system.
109 Results obtained in this work will allow us to hypothesize how these relationships could be
110 involved in the morphology of the human skull.

111

112 **MATERIAL AND METHODS**

113 The sample analysed in this study comprises twelve human skulls of known age and
114 sex divided into two subgroups: 6 specimens in the subadult group and 6 specimens in the
115 adult group (Table 1). All specimens belonged to the Anthropological Collection of the
116 University of Coimbra (Portugal). Individuals with malformations, traumatismos, or alveolar
117 bone resorption caused by tooth loss during life were excluded.

118 Obtaining the bone modeling pattern requires the microscope analysis of the bone
119 surface to identify bone formation and resorption fields. The best preserved half part of both
120 facial skeleton and mandible was employed in the analyses. We have used a non-destructive
121 methodology that involves the replication of the bone surface and the microscope analysis of
122 these replicas (Martinez-Maza *et al.*, 2010; see also Bromage, 1989). Specimens were first
123 cleaned with 60% alcohol applied with a smooth hair brush to eliminate any particles
124 adhering to the microrelief of the bone. Second, the negative impressions of the periosteal
125 bone from the facial skeleton and the mandible were made using a low-viscosity silicone
126 (Exaflex injection type 3 low viscosity; DVD Dental, SA, Spain). Negative impressions were

127 made independently from anatomical regions of the facial skeleton (glabella, superciliar arch,
128 nasal bones, nasomaxillary region, zygomatic bone) and the mandible (buccal and lingual
129 side of the symphysis, mandibular corpus, and ramus) to fit the microscope's size limitations
130 and to facilitate the manipulation during observation. Once silicone was cured, the negative
131 cast was removed from the bone surface and delimited with a retaining wall elaborated with a
132 silicone Optosil P plus and Optosil Xantopren (DVD Dental SA, Spain). Finally, positive
133 replicas of each anatomical region were generated using the polyurethane resin Feropur
134 (Feroqa, SA, Spain). Replicas were then coated with gold (sputter coater SC510 BIORAD)
135 prior to observation under a reflected light microscope (Olympus BX51TRF microscope
136 equipped with an Olympus DP11 digital camera) using a 20 X objective (Martinez-Maza et
137 al., 2010). To facilitate the localization of the remodeling microfeatures of the bone surface, a
138 grid of 5X5 mm squares was drawn on the surface of the gold-coated replica using a sharp
139 permanent pen. Each square was referred to by a coordinate (x,y) starting on the inferior left
140 square (1,1). This grid and the outline of the anatomical region were drawn on a paper to
141 record the data from the microscope.

142 The microscope analysis of the replicas from the periosteal bone surfaces allowed us
143 to identify and map the fields of growth modeling activities following the criteria provided by
144 Martinez-Maza et al. (2010; see also Bromage, 1989). Briefly, bone forming surfaces are
145 characterized by mineralized collagen fibre bundles produced by osteoblasts (Figure 1a;
146 Boyde, 1972; Bromage, 1989; Martinez-Maza et al, 2006; Martinez-Maza et al., 2010) and
147 bone resorbing surfaces showed Howship's lacunae produced by the osteoclasts (Figure 1b;
148 Boyde, 1972; Bromage, 1989; Martinez-Maza et al., 2010). Bone surface also showed eroded
149 surfaces characterized by several marks associated to the manipulation of the skulls such as
150 trampling, tool marks, fissures or writing marks, where neither bone formation nor resorption
151 features could be identified. From these data, modelling patterns for each individual were

152 drawn. Following previous works, generalized modeling patterns for the subadult and the
153 adult groups were established through the identification of intraspecific similarities in the
154 bone modeling field distribution of each anatomical region of the facial skeleton and mandible
155 (Enlow and Hans, 1996; Bromage, 1989; Rosas and Martinez-Maza, 2010; Martinez-Maza et
156 al., 2011).

157

158 **RESULTS**

159 Schematic bone modeling maps of subadult and adult specimens analysed in this study
160 are represented in Figures 2 and 3. Individual patterns show bone modeling fields with
161 variable size and shape, irregular boundaries, and patchy distribution. Even though different
162 specimens show eroded surfaces lacking information, histological data recorded from the
163 facial and mandibular regions have allowed us to elaborate generalized bone modeling
164 patterns for adults and subadults (Figure 4). A detailed description of the modeling fields
165 identified in the facial skeleton and the mandible is provided. Finally, we compare the
166 generalized bone modeling patterns of subadult and adult groups.

167

168 *Facial skeleton: subadult specimens*

169 The upper region of the facial skeleton (glabella and superciliar arch) is mainly
170 depository. Small resorption fields are only found in the superciliary arch-glabella contact
171 area close to the frontonasal suture in individuals 101 and 218, and in the inferior area of the
172 superciliary arch of specimen 100A. In the nasal bones, depository surfaces are present in all
173 specimens but in 126 and 100A, which present resorptive fields close to the pyriform
174 aperture. The nasomaxillary region shows high variability in the distribution of modeling
175 fields respect to other facial regions. This region displays predominantly resorptive surfaces in
176 the maxillary bone and depository surfaces in the nasal or frontal processes in individuals 218

177 and 101. This last specimen also presents small bone formation fields in the canine fossa
178 region close to the infraorbital foramen and in the lateral margins of the nasal aperture.
179 Specimen 100 shows bone resorption both in the nasomaxillary bone and in the nasal process,
180 while tiny depository surfaces are found close to the frontonasal suture and two fields in the
181 alveolar region of the maxilla. Specimens 284 and 126 show similar patterns characterized by
182 bone formation fields in the nasal process, in the lateral margins of the nasal aperture, in the
183 zygomaticomaxillary suture, and small depository fields in the canine fossa area. On the
184 contrary, specimen 100A shows mainly depository surfaces both in the nasal process and in
185 the maxillary bone, while resorptive surfaces are found close to the lacrimal area, in the lateral
186 margins of the nasal aperture, in the canine fossa area, and in the zygomaticomaxillary suture.
187 The zygomatic bone in all specimens displays primarily depository surfaces but three
188 specimens show bone resorption activity in the orbital margin of the frontal process either
189 close to the glabella (specimen 100) or extending from the zygomaticomaxillary suture to the
190 level of the infraorbital foramen (specimens 126 and 100A).

191 *Facial skeleton: adult specimens*

192 The bone modeling map of the upper facial region is characterized by bone formation
193 surfaces. Both the glabella and the superciliar arch regions are entirely depository in specimen
194 52, whereas specimens 92, 98, 144, and 342 show bone resorption fields in the glabella and in
195 the area between the glabella and superciliar arch and even in the frontonasal suture
196 (individuals 92 and 144). The remaining specimen (46) shows eroded bone surfaces in most
197 of the glabella and superciliar arch regions but small resorption fields are identified in the
198 glabella-superciliar arch region, and tiny bone formation fields can be identified in the
199 frontomaxillary suture and in the upper region of the superciliar arch. The nasal bones are
200 characterized by bone formation surfaces. This region is entirely depository in specimens 46
201 and 342, while in specimens 144 and 52 small resorptive fields are observed close to the

202 pyriform aperture and in the frontonasal suture area (specimen 144). On the contrary,
203 specimens 92 and 98 show predominantly bone resorption fields of variable size. The nasal
204 process of the nasomaxillary bone is also characterized by bone formation surfaces occupying
205 the whole area in specimens 98 and 342, while specimens 46, 92, 52, and 144 show small
206 resorption fields in the area between the frontal process and the maxillary body, and
207 distributed from the orbitary lateral margin to the lateral margin of the nasal aperture. The
208 specimen 144 also displays resorptive surfaces along the lateral orbital margin. The studied
209 specimens display a highly similar distribution of the growth fields in the maxilla. This facial
210 region is predominantly depository with bone resorption fields extending from the infraorbital
211 foramen to the canine alveolus (46, 92, 98, 342, and 52). Small resorbing surfaces are also
212 observed close to the nasal process in specimens 46, 52, 144 and 92, in the zygomatic
213 nasomaxillary suture (specimens 46 and 92), and in the lateral-inferior margin of the nasal
214 aperture (specimens 144 and 52). On its part, the zygomatic bone shows some variability,
215 being mainly depository in specimens 46, 98, 52 and 342, while in specimens 92 and 144
216 bone formation is reduced to the infraorbital foramen area. Resorption fields are observed in
217 the zygomatic maxillary suture in individuals 46, 92 and 98, also along the inferior margin of
218 the bone zygomatic to the temporal zygomatic suture in 92 and 98, and in the area extending
219 from the zygomatic maxillary suture to the infraorbital foramen level in specimen 46. The
220 specimen 92 displays bone resorption activity along the lateral orbital margin to
221 frontozygomatic suture. In this suture a resorption field is also observed in the specimen 144.

222

223 *Mandible: subadult specimens*

224 Among subadults, bone modeling activity is preserved in the mandibles of specimens
225 284 and 126, whereas specimens 101, 100A, 126, and 100 present a combination of eroded
226 surfaces and modeling fields with variable size and distributed along different mandibular

227 regions. In the symphyseal region, specimens 284 and 126 display predominantly bone
228 formation fields from the alveolar process to the inferior symphyseal border, whereas the
229 specimen 100A shows small depository fields in the mental fossae at the level of the central
230 incisors. All specimens show bone resorption fields in the alveolar process of the buccal side.
231 Small resorptive fields are also observed above the mental protuberance and at the level of the
232 canine in specimens 101 and 100A and in the mental fossae in individuals 100, 126, and 218.
233 The lingual side of the symphyseal region is characterized by depository fields distributed
234 both in the alveolar process and in the basal component in specimens 284, 126, and 101,
235 whereas depository fields of variable size are observed in the lingual alveolar process of
236 specimens 218 and 100, in the sublingual fovea of 100 and 100A, and in the inferior border of
237 specimen 100. Resorptive fields are restricted to the alveolar process of specimen 218, the
238 sublingual fovea of specimens 101 and 284, and the inferior border of specimen 284.

239 Subadult mandibular corpus is characterized by depository surfaces in the buccal side
240 and resorbing surfaces in the lingual side. However, some resorbing fields are found in the
241 buccal side in the alveolar process at the level of the second premolar in specimens 100A and
242 284, and in the basal component in the anterior region of the corpus of specimen 101, close to
243 the mandibular foramen in specimens 101 and 126, in the posterior region of the corpus in the
244 oblique line area of specimens 284 and 100A, and in the inferior region as a stripe of small
245 resorptive fields extending from the symphyseal region to the ramus of specimens 100A. On
246 its part, specimen 100 shows a high degree of erosion, but preserves resorption surfaces in the
247 alveolar process at the level of the incisors and the canine and close to the anterior border of
248 the ramus. At the lingual side, the sublingual fossa is characterized by bone resorption fields
249 in the premolar and molar area in specimens 218, 101, and 284 and in the molar region of
250 specimens 100 and 100A. Conversely, all specimens display depository surfaces in the
251 anterior area of the sublingual fossa at the level of the lateral incisors and the canines, from

252 the alveolar process to the mylohyoid line. The submandibular fossa is also characterized by
253 depository fields in specimens 101, 284, 100, and 100A, while erosion precluded obtaining
254 histological data from specimen 218. The lingual side of specimen 126 show a particular
255 modeling pattern characterized by bone formation surfaces in the sublingual fossa, whereas
256 the submandibular fossa is predominantly resorptive with depository fields at the level of the
257 first premolar and second molar.

258 In the mandibular ramus, the buccal side is predominantly depository in specimens
259 218, 101, 284, and 126, whereas in specimens 100 and 100A this region is characterized by
260 bone resorption surfaces. The bone formation activity in the specimens 218, 101, 284, and
261 126 is distributed as large (284 and 126) or small (218 and 101) fields throughout the buccal
262 side of the ramus. Among them, specimens 101, 284, and 126 display resorbing fields in the
263 anterior border of the ramus, the coronoid process and the condyle neck, and also, in the
264 specimen 284, bone resorption fields extend as a diagonal stripe from the coronoid until the
265 angle of the ramus. The remaining two specimens -100 and 100A- are characterized by
266 resorbing surfaces although bone formation is observed in the area between the coronoid
267 process and the condylar neck, and, in the specimen 100A, close to the angle of the mandible.
268 In the lingual side of the ramus, bone resorption activity predominates. Resorption fields
269 appear in the area between the anterior border and the endocoronoid crest of specimens 218,
270 284, 100, and 126, along the posterior region from the condyle neck to the angle of the ramus
271 in individuals 218, 101, and 126, and in the area associated to the pterigoideus internus from
272 which extend to the mandibular corpus in all specimens except in specimen 100. Depository
273 surfaces are observed close to the mandibular foramen between the condyle and the coronoid
274 in specimens 218, 101, 284, and 126, and in the corpus-ramus contact area of specimens 101,
275 284, and 126. Three specimens -284, 100, and 126- also display small depository fields below
276 the mandibular foramen and in the mylohyoid groove.

277 *Mandible: adult specimens*

278 The symphyseal region shows resorptive fields in the alveolar component of the
279 buccal side of specimens 46, 92, and 144, whereas specimens 52, 98, and 342 display
280 predominantly bone formation fields. The basal component of this region is always
281 depository, although specimen 342 also presents small resorbing fields at the mental fossa.
282 Similarly, the lingual side is characterized by depository surfaces in the alveolar process, but
283 specimens 46, 52, 98, and 144 also show small resorptive fields. The lingual basal component
284 of the symphysis mainly displays bone formation fields with resorptive fields in the mental
285 spine and in the digastric fossa regions. In specimens 52, 92, 98, and 144 resorptive activity
286 is also identified in the sublingual fossa.

287 The mandibular corpus is predominantly depository. In its alveolar component, bone
288 resorption activity is just found at the level of the canine of specimen 46, the premolar of 92,
289 and the molar regions of specimens 92 and 98. On the other hand, the basal component of the
290 corpus displays small resorptive fields close to the mental foramen area in specimens 46 and
291 342, in the contact region between the mandibular corpus and the ramus in specimens 46, 92,
292 98 and 144, and as a large stripe of resorptive fields along the inferior region of the corpus
293 from the premolar area to the ramus in specimens 98 and 144. In the lingual side of the
294 corpus, specimens 46, 52, and 342 display depository surfaces in the anterior region of the
295 sublingual fossa extending from the symphyseal region to the premolar region. Small
296 depository surfaces are also identified in the molar region close to the mylohyoid line of all
297 specimens but 342, and in the alveolar component of specimens 92, 98, and 144. The
298 premolar-molar region of the sublingual fossa of all individuals is characterized by bone
299 resorption fields. The submandibular fossa displays depository surfaces along the mylohyoid
300 line area and throughout the molar area in specimens 46, 98, and 342. Small depository
301 surfaces are also identified in the anterior part of the submandibular fossa in specimens 46,

302 92, 98, and 342. A large field of bone resorption activity is observed in the anterior area of
303 this fossa at the level premolar level in specimen 46, whereas small fields are identified in the
304 first molar level in 144 and 342 and in the area extending from the symphyseal region to the
305 ramus in specimen 98.

306 The adult mandibular ramus shows bone resorption surfaces in the buccal side of
307 specimens 46, 52, 92, and 144, whereas specimens 98 and 342 are characterized by depository
308 surfaces. On the one hand, resorbing activity is identified in the coronoid area in specimens
309 46, 92, 98, 144 and 52, in the condyle neck in 46, 92, 98, and 52, along the area running
310 parallel to the posterior border in 46, 92, 52 and 342, in the angle of the ramus in 144 and 52,
311 and close to the inferior border in 46, 98, 144, and 52. On the other hand, depository surfaces
312 are observed in the coronoid area in specimens 98 and 342, in the mandibular notch area in 92,
313 98, and 342, in the condylar neck in 98, 52, and 342, along the area running parallel to the
314 posterior border in specimen 98, and in the gonial region of specimen 342. The lingual side of
315 the adult ramus displays predominantly bone formation activity. Bone resorption activity is
316 located in the area between the anterior border and the endocoronoid crest in all specimens, in
317 the neck of the condyle of specimens 46, 92 and 98, in the area parallel to the posterior border
318 of specimens 46, 92, 98, and 144, and small resorptive fields in the mandibular notch area in
319 46, 92, 52, and 342. All specimens also display resorbing surfaces in the area associated to the
320 pterigoideus internus and in the corpus-ramus contact area.

321

322 The generalized bone modelling patterns for subadult and adult groups (Figure 4) are
323 obtained through the identification of intraspecific similarities in the bone modelling field
324 distribution of each anatomical region from the facial skeleton and mandible (Enlow and
325 Hans, 1996; Bromage, 1989; Rosas and Martinez-Maza, 2010; Martinez-Maza et al., 2011).
326 The subadult face generalized pattern shows bone formation fields in the upper (glabella and

327 superciliar arch) and middle face (nasal bones and frontal apophysis of the maxillary bone),
328 whereas bone resorption fields extends throughout the lower face (maxillar bone) and the
329 frontal process of the zygomatic bone. In the subadult mandible, the buccal side is
330 characterized by depository surfaces but resorption fields are identified in the alveolar
331 component of the symphyseal region, the coronoid region and the condyle neck. In the lingual
332 side, the anterior region of the mandible and the mandibular notch area are depository
333 whereas the molar region in the submandibular and the sublingual fossae is resorptive.

334 In adults, the generalized pattern of the facial skeleton is predominantly depository but
335 bone resorption activity, comparing with subadult pattern, is reduced to small fields in the
336 glabella, in the frontal apophysis of the maxillary bone and in the frontal apophysis of the
337 zygomatic bone (orbital margin). The resorbing activity of the lower face extends from the
338 canine fossa and along the inferior border of the zygomatic bone. The adult mandible shows
339 in the buccal side resorption activity in the alveolar component of the symphyseal region,
340 along the inferior region of the corpus, and a large field in the corpus-ramus contact area that
341 extends from the inferior margin to the coronoid region. The condylar neck and the
342 mandibular angle region show small resorptive fields. Unlike subadult specimens, the lingual
343 side is characterized by bone formation surfaces. The symphyseal region shows small
344 resorptive fields in the digastric fossa and mental spine region. In the lingual mandibular
345 corpus, the resorption activity is located in the molar region of the submandibular fossa and
346 extends by the coronoid region. A large resorptive field is identified in the gonial region and
347 close to the condyle neck.

348

349 **DISCUSSION**

350 In the present study, we have examined the postnatal growth dynamics of the human
351 facial skeleton and mandible through the analysis of the bone growth modeling activity. The

352 bone modeling patterns from subadult and adult specimens show differences in the
353 distribution of growth fields that demonstrate postnatal changes in bone growth dynamics.
354 Integration of the modelling data from the different anatomical elements informs us about the
355 general growth dynamics of the whole skull and its relationships with ontogenetic postnatal
356 changes of the craniofacial system.

357

358 **Bone growth dynamics in the subadult face and mandible**

359 The modelling pattern of the face and the mandible from the subadult specimens
360 established here is similar to the pattern described by Enlow (1982). On the one hand, the
361 facial skeleton is characterized by depository surfaces in the upper (supraorbital region) and
362 middle face (orbital and nasal regions) and bone resorption fields in the lower face
363 (nasomaxillary region). According to this map, the upper and the middle face grow in a lateral
364 and forward direction, whereas the zygomatic region grows laterally and is relocated
365 posteriorly in agreement with the resorbing surfaces present at the orbital margins. The lower
366 face shows complex growth dynamics related with the preservation of a functional nasal
367 cavity. As reported by Enlow (1982), resorption in the nasomaxillary region occurs
368 simultaneously to bone formation in the posterior region of the face (specifically in the
369 craniofacial sutures) and in the nasal cavity floor and palate. Consequently, the lower face
370 results in a downward or vertical growth of the maxilla, the formation of the *canine fossa*, a
371 depression on the external surface of the maxillary bone, and the increase in height of the
372 nasal cavity (Kurihara et al., 1980; Enlow and Hans, 1996; McCollum and Ward, 1997).

373

374 On the other hand, the mandible pattern is characterized by depository surfaces in the
375 symphyseal region and the anterior corpus, whereas the posterior region of the corpus and the
376 ramus show complex modelling patterns. According to these data, the mandible shows a

377 forward growth associated to the deposition in the symphysis and the corpus, as well as to the
378 lengthening of the posterior region of the corpus. At the same time, the ramus and the molar
379 region of the corpus show a main lateral growth, whereas the condyle and coronoid regions
380 show a forward growth with a posterior relocation of the ramus. Interestingly, the lingual side
381 of the corpus shows an opposite pattern to that proposed by Enlow (1982) –resorption in the
382 sublingual fossa and the region anterior to the mandibular foramen, and formation in the
383 submandibular fossa– suggesting a marked lateral growth of the molar region in the
384 mandibular corpus and ramus. Other differences regarding the extension of the resorbing
385 surfaces in the buccal side of the ramus could be considered artefacts due to the variability of
386 the distribution of modelling fields observed in the human mandible (Enlow and Harris, 1964;
387 Kurihara et al., 1980; Hans et al., 1995). It is also worth mentioning that the symphyseal
388 region presents a human-specific resorption field in the alveolar component of the buccal side
389 related to the dental movements and the mental growth, and being involved in the
390 development of the human chin (Enlow and Hans, 1996).

391 Variability in the distribution of the modelling fields is mainly observed at the anterior
392 lower face and at the mandibular ramus. Differences in the distribution and the extension of
393 the resorption fields of the anterior face agrees with the modelling data provided by Kurihara
394 et al. (1980) for humans up to 14 years old, but disagrees with the mainly-depository anterior
395 lower face observed by McCollum (2008). As annotated by Kurihara et al. (1980) and later by
396 McCollum (2008), variability in the modelling maps from this facial region could be due to
397 morphological variations associated to differences in geographic origin. Variability in the
398 mandible ramus involves the extension and the location of the resorption fields in the
399 coronoid and the condyle neck, due to lateral adjustments while growing upward and
400 relocating posteriorly. Besides these two main areas, variability is also observed in the buccal
401 symphyseal region -previously reported by Kurihara et al (1980)- and in the mandibular

402 corpus -opposite to the general pattern established here, individual 126 submandibular fossa
403 pattern resembles to that established by Enlow and Hans (1996)-.

404

405 **Bone growth dynamics in the adult face and mandible**

406 We have established for the first time, to our knowledge, the bone modelling pattern of
407 the face and the mandible from adult humans. The facial pattern is mainly depository with
408 resorption surfaces restricted to the nasal region, the canine fossae, and the inferior margin of
409 the zygomatic region. General growth directions from this pattern indicate a lateral,
410 downward and forward growth of the whole adult face. Like in subadult specimens, the
411 nasomaxillary region shows complex growth dynamics associated to the functional spaces
412 such as the nasal and the oral cavities (Moss, 197x). Bone resorption in the nasal region could
413 be associated with the increase in high of the nasal aperture (CITA) and the forward
414 projection of this region (CITA). Although there is no data about the nasal floor and palate for
415 adult specimens, the modelling map obtained in our study and the morphometric data
416 obtained in previous works (CITAS) allow us to hypothesize that the lower face shows a
417 downward and forward growth of the maxilla associated to the increase of the nasal cavity.
418 Resorbing surfaces in the anterior nasomaxillary region of the adult face are restricted to the
419 area of the canine fossae, likely related to its development.

420 In the adult mandible, the symphysis and the anterior region of the corpus are mainly
421 depository with resorbing surfaces restricted to the alveolar component of the buccal side of
422 the symphysis, resembling the pattern of subadult specimens. Slight differences are found in
423 the lingual side of the symphysis which show resorption fields in sites associated to muscle
424 attachment (gastricus, genioglossus, geniohyoideus and the anterior part of the mylohyoideus
425 muscles). The pattern of the posterior region of the corpus and the ramus highly differs from
426 the subadult patterns established in the present and previous works (Enlow and Hans, 1996;

427 Kurihara et al., 1980). In the adults, resorption extends to cover, in the buccal side, the
428 posterior region of the *corpus* and the anterior region of the *ramus*, and, in the lingual side,
429 the submandibular fossa of the *corpus*, and the coronoid region and the lower half (gonial
430 area) of the *ramus*. This map indicates a forward growth direction of the symphysis and a
431 lateral growth of the molar region of the *corpus*, whereas the anterior region of the *ramus*
432 grows in a posterior and medial direction. The posterior region of the *ramus* experiments
433 complex growth dynamics characterized by a lateral growth of the gonial area, a medial
434 growth of the mandibular notch area, and a lateral and medial growth of the condyle area.
435 These growth directions indicate that the lower part of the *ramus* is taking a vertical position
436 while the upper area increases in width and grows backwards.

437 The modelling pattern of the facial skeleton and the mandible varies less in adult than
438 in subadult specimens. Variability is observed in the extension of the resorption fields of the
439 anterior nasomaxillary region and the mandibular *ramus*, as observed in subadults. As
440 proposed by Kurihara et al. (1980) and McCollum (2008) for subadult specimens, we
441 hypothesize that these variations could respond to individual differences in functional or
442 morphological characteristics (Kurihara et al., 1980; Enlow and Hans, 1996).

443

444 **Postnatal changes in the growth dynamics of the human face**

445 According to the data obtained in the present study, the facial skeleton and mandible
446 from both subadult and adult specimens show a general downward and forward growth, in
447 agreement with Enlow and Hans (1996). However, bone modelling patterns differ among both
448 age groups, showing a marked spatial gradient, from a anterior region of the maxilla where
449 most changes concentrate to the almost constant facial regions in the proximity of the
450 neurocranium. Interpretation of these ontogenetic changes would benefit from an integrative
451 perspective taking into consideration how the different skeletal components within the

452 craniofacial system interact to maintain the functional and structural balance whereas they
453 increase in size during the postnatal development (Enlow and Hans, 1996; Moss and Young,
454 1960; Moss, 1962).

455 During the subadult stage, the facial skeleton experiences a downward growth and a
456 forward displacement, together with the lengthening of the maxilla. This growth and
457 displacement of the facial block is accompanied by an upward maxillary rotation
458 (airorhynchy) due to the higher bone growth in the craniofacial sutures that attach the midface
459 to the basicranium than in the anterior region of the maxilla (Björk and Skieller, 1976;
460 Bromage, 1989; McCollum and Ward, 1997). This rotation of the premaxilla would be
461 countered by a downward rotation through compensatory resorption activity in the external
462 surfaces of the anterior region of the maxilla (Björk, 1968; Björk and Skieller, 1976; 1983;
463 see also Bromage, 1989; McCollum and Ward, 1997 and references there in). The resulting
464 downward facial growth vector contributes to the relative orthognathy in humans (Bromage,
465 1989). Simultaneously, the whole mandible is displaced forward and downward to
466 compensate the displacements of the maxilla and to maintain the occlusal plane (Moss, 197x;
467 Enlow and Hans, 1996). The forward displacement of the face becomes balanced through the
468 growth of the posterior region of the mandibular corpus, whereas the vertical growth is
469 compensated by the increase in height of the *ramus* and, particularly, the condyle (Enlow and
470 Hans, 1996). During this displacement, the mandibular *corpus* increases in width at the
471 anterior region, whereas the molar region and the *ramus* show a lateral drift. The lateral drift
472 and the vertical growth of the *ramus* have been related to the growth of the basicranium as a
473 way to keep the mandible in contact with the neurocranium through the temporomandibular
474 joint.

475 With adulthood, the modelling pattern changes reflecting the biological changes that
476 take place with maturation. Most important changes occur in the anterior region of the face,

477 where the resorbing surfaces that occupy most of the immature nasomaxillary region become
478 restricted to the canine fossae whereas formation occupy the remaining surface. This
479 modelling pattern would indicate a direct forward growth of the nasomaxillary complex
480 during adulthood opposite to the primary displacement that takes place in immatures.
481 Modelling changes run parallel to the fusion of the craniofacial sutures and the end of the
482 brain growth that occur around 18 to 20 years after birth (Madeline and Elster, 1995; Björk,
483 2007). Considering that the posterior growth of the face in immature individuals occur by
484 bone formation at the craniofacial sutures (Enlow and Hans, 1996), the fusion of these sutures
485 and the subsequent arrest of the bone growth in the area would limit the growth of this
486 posterior region of the facial skeleton. Thus, the modelling pattern and the biological
487 constraints indicate that the facial growth in the adult stage is restricted to the anterior region
488 and suggest a forward growth of the whole facial skeleton with an increase in the height of the
489 nasal region.

490 The mandible also responds to these developmental changes, as reflected in its
491 modelling pattern. Ontogenetic changes concentrate in the *ramus*, a region that increases in
492 height at a rate similar to the nasomaxillary region, resulting in a increase of the nasal cavity
493 while it maintains the occlusal plane. The *ramus* also grows laterally and medially to keep the
494 vertical position and the contact with the neurocranium through the temporomandibular joint
495 (Enlow and Hans, 1996). As the neurocranium and basicranium stops growing in the adult
496 stage, the distance between the mandible fossae becomes established and the condyles would
497 adapt to this distance changing the growth of the condyles and maintaining a functional
498 position.

499 Changes in the modelling pattern of the face and the mandible during adulthood have
500 been related to the necessity of increasing the volume of the oral and nasal cavities to cope the
501 physiological requirements of the organism. It has been suggested that growth and

502 development of the craniofacial complex is related to the nasal respiratory function (Hall,
503 2005; Chinn *et al.*, 2006; Weinstein, 2008; Gungora and Turkkahramanb, 2009). The
504 coordinated development of the respiratory system and body size is likely a factor that could
505 influence the facial growth particularly for the nasomaxillary complex and the mandible (see
506 Bastir, 2008 and references therein). In addition, the craniofacial growth is also related to size,
507 shape, and energetics of the entire body (Bastir, 2008). In this line, the forward growth of the
508 anterior face that occurs during the adulthood would reflect that the neurocranium has stop
509 growing but the body still grows together with all its physiological requirements.

510 In conclusion, our results demonstrate postnatal changes in the growth dynamics of the
511 facial skeleton and the mandible. We hypothesize that these changes are related to biological
512 events occurred in the craniofacial system such as the fusion of the craniofacial sutures, or the
513 reaching of the adult size of the brain and the neurocranium. Thus, in the adults, a new
514 relationship among skeletal elements of the skull emerges but the face needs to continue
515 growing, increasing the nasal and oral cavities in order to maintain a functional and structural
516 balance.

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519

520 **ACKNOWLEDGEMENTS**

521 We thanks to Eugenia Cunha for access to the anthropological collection of *Homo sapiens*
522 holded in the (Universidade de Coimbra, Portugal). This study was supported by the projects
523 xxx. CMM

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694

695 **TABLE**

696 **Table 1.** List of the *Homo sapiens* specimens from the Anthropological Collection of the
 697 University of Coimbra (Portugal) analysed with Reflected Light Microscopy.

Specimen	Age (years old)	Age group	Sex
101	12	Subadult	Female
218	10	Subadult	Female
284	17	Subadult	Female
100	7	Subadult	Male
100A	11	Subadult	Male
126	8	Subadult	Male
52	38	Adult	Female
144	29	Adult	Female
342	28	Adult	Female
46	38	Adult	Male
92	27	Adult	Male
98	24	Adult	Male

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713 **FIGURE LEGENDS**

714 **Figure 1.** Bone formation (left) and resorption (right) surfaces identified in the sample of
715 *Homo sapiens* analysed in this study. Image on left shows a bone formation surface from the
716 buccal side of the mandibular corpus region (specimen 126), which is characterized by
717 collagen fiber bundles. Image on right shows a bone resorption surface from the maxilla
718 (specimen 218) characterized by Howship's lacunae. Scale bar: 100 μ m.

719

720 **Figure 2.** Schematic bone modeling patterns from the specimens of the subadult group. Black
721 colour: bone formation surfaces; grey colour: bone resorption surfaces.

722

723 **Figure 3.** Schematic bone modeling patterns from the specimens of the adult group. Black
724 colour: bone formation surfaces; grey colour: bone resorption surfaces.

725

726 **Figure 4.** Generalized bone modeling patterns from subadult and adult humans. Stippling
727 areas represent bone deposition and grey areas represent bone resorption. Black arrows show
728 the direction of growth by bone formation and white arrows the direction of growth by bone
729 resorption.

730

731 **Figure 5.** Figure shows the growth vectors inferred from the generalized bone modeling
732 patterns from subadult and adult humans. Black arrows show the direction of growth by bone
733 formation and white arrows the direction of growth by bone resorption.