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# New Thoughts on Pediatric Genetic Obesity: Pathogenesis, Clinical Characteristics and Treatment

## Approach

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Stefano Stagi, Martina Bianconi,

Maria Amina Sammarco, Rosangela Artuso,

Sabrina Giglio and Maurizio de Martino

Additional information is available at the end of the chapter

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**Abstract**

10 Historically, some genetic syndromes and monogenic forms of obesity have been  
11 identified by clinical features and by sequencing candidate genes in patients with severe  
12 obesity. The phenotypic expression of genetic factors involved in obesity is variable,  
13 thereby allowing to distinguish several clinical pictures of obesity. Monogenic obesity  
14 is described as rare and severe early-onset obesity with abnormal feeding behavior and  
15 endocrine disorders. Many of the findings emerged from studying families who  
16 displayed a classical Mendelian pattern of inheritance. On the contrary, patients with  
17 syndromic obesity show a various degree of intellectual disability, different dysmorphic  
18 features, and organ-specific abnormalities. But to date, not all involved genes have been  
19 identified so far. New diagnostic tools, such as genome-wide studies, array CGH, and  
20 whole-exome sequencing, have highlighted more complex models of inheritance, and  
21 even more candidate genes were identified. This increase of knowledge may provide  
22 insights into the mechanisms involved in the regulation of body weight and finally lead  
23 to specific treatments. In these patients, hyperphagia is often a primary phenotypic  
24 component. Substantial gaps in understanding the molecular basis of inherited  
25 hyperphagia syndromes are present today with a lack of mechanistic targets that can  
26 serve as a basis for pharmacologic and behavioral treatments. We have evaluated  
27 retrospectively the literature data on weight, body mass index (BMI), clinical features,  
28 treatments, and treatment response in pediatric patients with forms of genetic obesity.  
29 However, this chapter provides an updated picture of emerging knowledge outlined  
30 by the more comprehensive genetic approaches, trying to outline more candidate genes  
31 for these forms of genetic obesity. Relevant papers will be identified through systematic  
32 searches of the PubMed, EMBASE and Cochrane databases. All published studies in the  
33 English language concerning these disorders will be evaluated. Keywords in the  
34 literature search will be entered in all combinations. Searches will be augmented by

1 manually reviewing the reference lists of all original articles and all systematic review  
2 articles, with each study being evaluated for inclusion.

3 **Keywords:** obesity, children, adolescence, next-generation sequencing, array CGH,  
4 pediatrics, diabetes, hyperphagia

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## 5 **1. Introduction**

6 The World Health Organization defines being overweight and obesity as a “clinical condition  
7 characterized by an abnormal or excessive fat accumulation that may impair health” [1]. In  
8 2014, an estimated 41 million children under the age of 5 were overweight or obese [1]. Once  
9 considered a problem only in high-income countries, being overweight and obesity are now  
10 dramatically on the rise in low- and middle-income countries, particularly in urban settings [1].

11 Therefore, obesity is considered a global epidemic and can cause serious health repercussions.  
12 In fact, in addition to causing a significant morbidity and premature mortality and to have  
13 psychological and social consequences, it is associated with medical conditions, such as type  
14 II diabetes (non-insulin-dependent diabetes mellitus or NIDDM), hypertension, coronary  
15 artery disease and many forms of cancer [2].

16 In order to create the best management programs and to determine novel therapeutic targets,  
17 it has become essential to understand the factors causing today’s rising epidemic of childhood  
18 obesity [3].

19 Obesity is a complex condition, caused by multiple factors. It is characterized by an altered  
20 energy system, determined by the interaction of biological, social, and behavioral factors that  
21 cause an increase in food intake and a reduction in energy expenditure [4].

22 This global epidemic and the increase of its prevalence show that this condition is the result  
23 not only of genetic causes, but also of environmental factors (high availability of palatable and  
24 energy dense foods) [4]. However, some individuals manage to maintain a healthy body weight  
25 in an “obesogenic” environment, but the weight gain may be determined by their genetic  
26 susceptibility [4].

27 Recently, major advances in obesity research emerged concerning the molecular mechanisms  
28 contributing to the obese condition. However, several studies and data concerning the genetics  
29 and other important factors in the susceptibility risk of developing obesity are becoming  
30 increasingly evident [5]; in fact, available data suggest that 40–77% of the observed variance  
31 in human body weight can be accounted for, by inherited factors [6–8].

32 The strongest risk factor for childhood and adolescent obesity is parental obesity [9]. The risk  
33 becomes especially elevated if both parents are obese [10]. On the contrary, the pattern of  
34 inheritance of monogenic obesity is different (which may or may not be related to specific  
35 syndromes). In fact, they are attributable to a Mendelian model which recognizes a rare

1 causative mutation to load a single gene that can be expressed in the heterozygous and  
2 homozygous state [11].

3 Patients can be affected by monogenic forms, in which obesity is the predominant feature but  
4 it is not associated with malformations, or by syndromic obesity: in the latter case, they show  
5 also a pattern of clinical features, including developmental delay, dysmorphic features,  
6 and/or other developmental abnormalities [12].

7 Furthermore, historically, some genetic syndromes and monogenic forms of obesity have been  
8 identified by clinical features and by sequencing candidate genes in patients with severe  
9 obesity. Many of the initial findings emerged from studying families who displayed a classical  
10 Mendelian pattern of inheritance; however, more comprehensive genetic approaches, such as  
11 genome-wide studies, array CGH, and next-generation sequencing examinations, have  
12 highlighted more complex models of inheritance, and ever more candidate genes were  
13 identified [13]. In broad terms, most cases of patients with genetic forms of obesity are  
14 oligogenic, determined by interaction between genetic and environmental factors. In these  
15 cases, the genetic make-up influences weight and the individual responses to nutrition and  
16 physical activity. In addition to this form of obesity, there are others caused by a single gene  
17 or it appears to be related to a specific syndrome. Monogenic obesity typically is caused by a  
18 single gene mutation with severe obesity as the main symptom; syndromic obesity, on the other  
19 hand, has many characteristics, of which obesity is one symptom [13].

20 The increase of knowledge about the functional and physiological features of these different  
21 obesity forms may provide insights into the mechanisms involved in the regulation of body  
22 weight and finally lead to specific treatments. In these patients, hyperphagia is frequently a  
23 primary phenotypic component. Substantial gaps in understanding the molecular basis of  
24 inherited hyperphagia syndromes are present today with a lack of mechanistic targets that can  
25 serve as a basis for pharmacologic and behavioral treatments.

26 The comprehension of the molecular mechanisms of obesity progressed enormously in the last  
27 years thanks to the development of faster and more precise genetic screening tools applied in  
28 cohort studies or in examinations with focus on subjects and their families.

29 Several clinical presentations in obesity depend on the genes involved:

- 30 1. Monogenic obesity, described as rare and severe early-onset obesity, associated with  
31 endocrine disorders. The impact of genetics is high and only little dependent on environ-  
32 mental factors.
- 33 2. Syndromic obesity that corresponds to severe obesity associated with additional pheno-  
34 types (mental retardation, dysmorphic features, and organ-specific developmental  
35 abnormalities). Prader-Willi (PWS) and Bardet-Biedl (BBS) syndromes are the two most  
36 frequently linked to obesity, but more than 100 syndromes are now associated with  
37 obesity.
- 38 3. Oligogenic obesity, characterized by a variable severity, partly dependent on environ-  
39 mental factors and the absence of a specific phenotype. This type of obesity is responsible  
40 for 2–3% in adults and children.

1 Rare genetic forms of obesity are important to be detected clinically because it allows to  
 2 progress in understanding the physiopathology of obesity. On the other hand, there is a specific  
 3 management of these forms of obesity provided by specialized and multidisciplinary teams.

## 4 2. Monogenic obesity

5 A “monogene” is by textbook definition, a gene with a strong effect on the phenotype (Men-  
 6 delian traits or Mendelian—single gene conditions), giving rise to a one-on-one relationship  
 7 between genotype and phenotype.

8 So, monogenic and not syndromic obesity is caused by a single mutation of a gene.

9 This form of obesity occurs in infancy and is often associated with additional behavior,  
 10 developmental or endocrinological disabilities, such as hyperphagia and hypogonadism;  
 11 however, significant developmental delays are not visible, and the obesity is often not  
 12 associated with other clinical manifestations [3, 6, 8, 13–17].

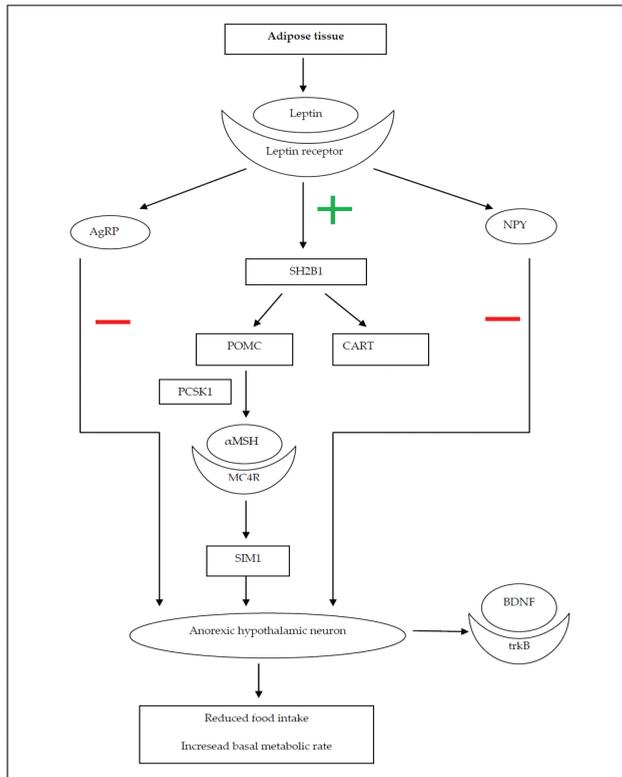
13 The types of monogenic obesity are summarized in **Table 1** [10–12, 18].

Monogenic obesity		
Gene name		Main distinguishing features in addition to obesity
LEP deficiency	<i>LEP</i>	Hypogonadism, absent or delayed puberty, frequent infections, undetectable serum leptin
LEPR deficiency	<i>LEPR</i>	Hypogonadism, absent or delayed puberty
SH2B2 deficiency	<i>SH2B1</i>	Severe insulin resistance and disproportionate to degree of obesity; in rare cases presence of developmental delay
POMC deficiency	<i>POMC</i>	Hypogonadism, absent or delayed puberty, hair and cute hypopigmentation, isolated ACTH deficiency
MC4-R deficiency	<i>MC4-R</i>	Accelerated growth, increased final height
PCSK1 deficiency	<i>PCSK1</i>	Hypogonadism, absent or delayed puberty, postprandial hypoglycemia, elevated plasma proinsulin, severe malabsorption in the neonatal period
SIM1 deficiency	<i>SIM 1</i>	Spectrum of developmental delay
BDNF/trkB deficiency	<i>BDNF o</i> <i>NTRK2</i>	Developmental delay, hyperactivity, impaired memory, impaired pain sensation
CART deficiency	<i>CART</i>	Anxiety and depression

14 Adapted with permission from Ramachandrapa and Farooqi [19].

15 **Table 1.** Main features of monogenic not syndromic obesity.

16 These types of monogenic obesity are caused by mutations in leptin–melanocortin hypothala-  
 17 mic pathway genes. These genes regulate the sense of appetite and hunger (**Figure 1**).



1

2 **Figure 1.** Appetite regulation: inhibitory (-) and favoring (+) mechanisms. Adapted with permission from Perrone et al.  
 3 [11].

4 **2.1. Congenital leptin deficiency (OMIM #614962)**

5 In 1997, two severely obese cousins (an 8-year-old female child with a weight of 86 kg and a  
 6 2-year-old male child with a weight of 29 kg) were reported from a highly consanguineous  
 7 family of Pakistani origin [20]. Despite their severe obesity, both children had undetectable  
 8 levels of serum leptin and a mutation in the gene encoding leptin mapped at 7q32.1. The disease  
 9 is caused by mutations in the *LEP* gene (OMIM \*164160) typically leading to defects in protein  
 10 synthesis or secretion, and therefore to the absence or very low blood levels of this hormone  
 11 [21–23].

- 1 However, recently the first cases of functional leptin deficiency have been described [23, 24].  
 2 This entity is characterized by detectable immunoreactive levels of circulating leptin, but  
 3 bioactivity of the hormone due to defective receptor binding [23, 24].
- 4 So, serum leptin may be a useful marker in patients with severe early-onset obesity as an  
 5 undetectable serum leptin is highly suggestive of a diagnosis of congenital leptin deficiency  
 6 due to homozygous loss of function mutations in the *LEP* gene [12]. Leptin-deficient subjects  
 7 are born of normal birth weight but exhibit rapid weight gain in the first few months of life  
 8 resulting in severe obesity [25].
- 9 Leptin deficiency causes the loss of appetite control, so it is associated with hyperphagia,  
 10 increased energy intake and aggressive behavior when food is denied. Other phenotypic  
 11 features include hypothalamic hypothyroidism, hypogonadotropic hypogonadism (because  
 12 leptin stimulates hypothalamic gonadotropin-releasing hormone [GnRH] production),  
 13 elevated plasma insulin, T-cell abnormalities (because leptin also stimulates the inflammatory  
 14 response and proliferation of T cells and cytokines Th1 mediated), and advanced bone age [26].  
 15 Currently, the prevalence of mutations in leptin is about 1% [12].
- 16 Leptin deficiency is entirely treatable with daily subcutaneous injections of recombinant  
 17 human leptin with beneficial effects on the degree of hyperphagia, reversal of the immune  
 18 defects and infection risk and permissive effects on the development of puberty [25]. The  
 19 major effect of leptin administration is the normalization of hyperphagia and enhanced satiety  
 20 [25, 27].
- 21 *2.2. Congenital leptin-receptor deficiency (OMIM #614963)*
- 22 In 1998 (1 year after the discovery of the congenital leptin deficiency), patients with similar  
 23 phenotypic characteristic of leptin deficiency, but with a high blood level of leptin, were  
 24 reported [28]. In these patients, a mutation in the leptin receptor (*LEPR*, OMIM \*601007),  
 25 mapped at 1p31.3, has been described [28].
- 26 One subsequent study has demonstrated that 3% of a group of patients with severe, early-  
 27 onset obesity had a pathogenic *LEPR* mutation, but blood levels of leptin were not very high,  
 28 suggesting that blood leptin levels cannot be used as a marker for leptin-receptor deficiency  
 29 [29].
- 30 In literature, many mutations of the leptin receptor are described. Most recently, three novel  
 31 mutations have been reported in the *LEPR* in two unrelated affected obese girls when latest  
 32 genetic analysis techniques like whole-exome sequencing and targeted sequencing have been  
 33 used for the mutational analysis in this gene [30, 31].
- 34 The clinical phenotypes associated with congenital leptin-receptor deficiency are similar to  
 35 those of leptin deficiency, with severe obesity from the first few months of the life, hypothala-  
 36 mic hypothyroidism and hypogonadotropic hypogonadism [12, 26].
- 37 On the contrary, in these patients, because of a non-functional *LEPR*, leptin treatment is  
 38 ineffective. Other factors could possibly bypass normal leptin delivery systems, but these are  
 39 not yet currently available for the treatment of these patients [32].

### 1 2.3. SH2B1 deficiency

2 The Src-homology-2 B adaptor protein 1 (*SH2B1*, OMIM \*608937) is a key intermediary in leptin  
3 signaling, promoting the activation of the leptin signaling pathway downstream of Janus  
4 kinase 2 (*JAK2*, OMIM \*147796) [15]. So, leptin-stimulated activation of hypothalamic JAK2 is  
5 dramatically attenuated in *SH2B1* knockout mice [33].

6 In 2010, it was described that the 220-kb 16p11.2 deletion (28.73–28.95 Mb) seen in three  
7 patients co-segregated with severe early-onset obesity alone [14]. This deletion includes a  
8 small number of genes, one of which was *SH2B1*, known to be involved in leptin and insulin  
9 signaling [12]. However, several mutations in the *SH2B1* gene have also been reported in  
10 association with early-onset obesity, severe insulin resistance and behavioral abnormalities  
11 in some patients [34].

12 The phenotype of the children with *SH2B1*-containing deletions is characterized by extreme  
13 hyperphagia and fasting insulin levels disproportionately elevated compared to age and  
14 obesity-matched controls [15]. As expected, obese *SH2B1* KO mice develop hyperglycemia,  
15 hyperinsulinemia, glucose intolerance, and insulin resistance and NIDDM [35]. Interestingly,  
16 central and peripheral SH2B1 seem to regulate insulin sensitivity and glucose metabolism  
17 independently of its action on body weight in man and mice [36].

18 In these patients, there is no specific treatment, but care must be taken in starting a specific  
19 follow-up on the hyperphagia, obesity and alteration of gluco-insulinemic metabolism.

### 20 2.4. POMC deficiency (OMIM #609734)

21 In 1997, a role of central melanocortin signaling in the control of energy homeostasis was  
22 known [37]. Proopiomelanocortin (POMC) acts on anorectic targets of leptin in the brain [38].  
23 The POMC, through to proconvertase 1 (PCSK1), is the precursor of  $\alpha$ -melanocyte-stimulating-  
24 hormone anorectic peptide ( $\alpha$ -MSH); the latter acts on melanocortin 4 receptor (MC4-R)  
25 anorectic neurons and suppresses the appetite and food intake [39].

26 Monogenic obesity from POMC deficiency manifests itself when there are homozygous null  
27 mutations. Heterozygous carriers of null *POMC* gene mutations have a significantly higher  
28 risk of being obese or overweight but are not invariably associated with obesity [19].

29 Since POMC is the precursor of adrenocorticotrophic hormone (ACTH) and melanocyte-  
30 stimulating-hormone anorectic peptide (MSH), POMC-deficient newborns have adrenal crisis  
31 and pale skin and hair. Also, POMC deficiency causes hyperphagia and childhood obesity [3,  
32 40]. The clinical features are comparable to those reported in patients with mutations in the  
33 receptor for POMC-derived ligands, MC4R (see below in the next chapter) [12].

34 Two important *POMC* mutations have been described in literature: the first is the rare mutation  
35 *R236G* that disrupts a di-basic cleavage site between  $\beta$ -MSH and  $\beta$ -endorphin, resulting in a  
36  $\beta$ -MSH/ $\beta$ -endorphin fusion protein that binds to MC4R but has reduced ability to activate the  
37 receptor [38, 41]. The second is a rare missense mutation in the region encoding  $\beta$ -MSH,  
38 *Tyr221Cys* that cannot bind to and activate signaling from the MC4R, and obese children

1 carrying the *Tyr221Cys* variant are hyperphagic and showed increased linear growth, features  
2 of MC4R deficiency [42].

3 Specific treatment was not available until January 2016, when the US Food and Drug Admin-  
4 istration awarded orphan drug status to the first  $\alpha$ -MSH-based therapy for obesity. The  $\alpha$ -MSH  
5 analog RM-493 [43, 44], also known as setmelanotide, was awarded orphan drug status for  
6 POMC deficiency and Prader-Willi syndrome [37].

### 7 **2.5. Melanocortin-4 receptor deficiency (MC4R)**

8 Among all forms of monogenic obesity, the most common is caused by MC4-R deficiency.  
9 Heterozygous mutations have been reported in many ethnic groups of obese patients and  
10 prevalence varies from 0.5 to 1.0% in obese adults, up to 6% in individuals with severe infantile  
11 onset obesity [45]. In 2014, a case of childhood obesity associated with compound hetero-  
12 zygosity for two mutations of *MC4R* gene (OMIM \*155541), mapped at 18q21.32, was descri-  
13 bed [46]. In the same year, another new inactivating homozygous mutation of the *MC4R* gene  
14 in a girl with the severe obesity and hyperphagia was reported [47].

15 Mutations of this gene are codominant with variable penetrance and expressivity in hetero-  
16 zygous carriers [48]. Both heterozygous and homozygous mutations in *MC4R* have been  
17 implicated in obesity, but extreme obesity is incompletely penetrant in heterozygous patients  
18 [3]. Also, in these patients, genetic and environmental factors influence the severity of obesity  
19 associated with mutations of *MC4-R*.

20 The main clinical features include hyperphagia in early appearance (but not as severe as that  
21 seen in leptin deficiency) and an increase in fat mass, lean mass and bone mineral density [45].  
22 These patients also have an accelerated growth that seems to be a consequence of hyperinsu-  
23 linemia which such patients present from the earliest periods of life. It is apparently not related  
24 to a dysfunction of the GH axis [3, 49]. Despite this early hyperinsulinemia, obese adult subjects  
25 who are heterozygous for mutations in the *MC4R* gene are not at increased risk of developing  
26 glucose intolerance and NIDDM compared to controls of similar age and adiposity [12, 45].

27 Currently, there are no specific therapies for the MC4-R deficiency, but these individuals may  
28 benefit from surgical therapies, which could be taken into consideration in adults [12].

### 29 **2.6. PCSK1 deficiency (OMIM #600955)**

30 Pro-protein convertases (PCs) are a family of serine endoproteases that cleave inactive pro-  
31 peptides into biologically active peptides [50]. Two of these pro-protein, proprotein convertase,  
32 subtilisin/kexin-type 1 (PCSK1) and PCSK2 are selectively expressed in neuroendocrine tissues  
33 and cleave pro-hormones such as POMC, thyrotropin-releasing hormone (TRH), GnRH,  
34 proinsulin, proglucagon [12].

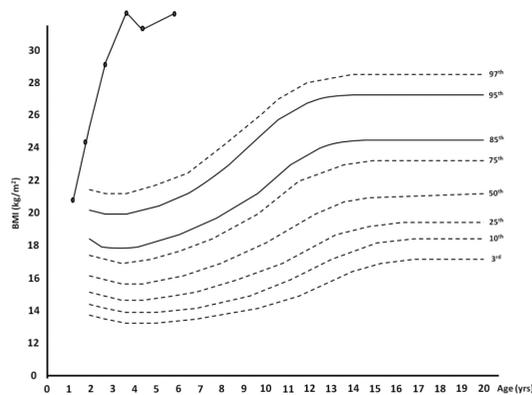
35 Patients with heterozygous or homozygous mutations in the *PCSK1* gene (OMIM \*162150),  
36 mapped at 5q15, present small bowel enteropathy, early-onset obesity and complex neuroen-  
37 docrine effects due to a failure to process the pro-hormones such as diabetes insipidus,  
38 glucocorticoid deficiency, hypogonadism, and altered glucose homeostasis [51, 52].

1 A typical characteristic of these patients is a history of severe intestinal malabsorption in the  
 2 neonatal period, probably due to altered cleavage of intestinal peptides in the enteroendocrine  
 3 cells [51].

4 Over the past few years, two meta-analysis about *PCSK1* mutations have been published: the  
 5 first in 2014 confirmed the association of *PCSK1* SNPs with obesity and provides the first  
 6 evidence that the association between *PCSK1* *rs6232* and obesity is stronger for childhood  
 7 obesity than for adult obesity; the second meta-analysis tried to study the association of *PCSK1*  
 8 variants *rs6232* and *rs6234/rs6235* with quantitative BMI variation and common obesity risk in  
 9 subjects from diverse ethnic groups. In this study, cohort age-group significantly modulated  
 10 the association between *rs6232*, *rs6234/rs6235* and obesity with the effect sizes for both SNPs  
 11 being stronger in children/adolescents than in adults.

12 It is thought also that the most common *PCSK1* variants predispose to obesity especially in an  
 13 "obesogenic" environment with free access to high-caloric food [53].

14 Currently, there are no specific therapies for the *PCSK1* deficiency, but these individuals  
 15 frequently required a prolonged course of parenteral nutrition therapy, particularly in the first  
 16 year of life [54]. However, exogenous administration of several hormone may be necessary in  
 17 relation to the hormonal deficiencies diagnosed [54].



18  
 19 **Figure 2.** Girl with 6q16.3 deletion involving *SIM1* gene. It is evident that the extreme increase of the BMI of the patient  
 20 and the reduction after the interdisciplinary approach.

21 **2.7. SIM1 deficiency**

22 Single-minded 1 (*SIM1*) is a transcription factor involved in the development of the supraoptic  
 23 and paraventricular nuclei, acting downstream signal cascade of MC4-R. Obesity and hyper-

1 phagia have been reported in a patient with a balanced translocation disrupting *SIM1* [55] and  
 2 multiple heterozygous missense mutations (6q16.3; OMIM \*603128) [56]. However, some  
 3 mutations of *SIM1* have incomplete penetrance and variable phenotype [57]. The similar  
 4 phenotype between patients with *SIM1* and MC4-R deficiency suggests that some effects of  
 5 *SIM1* are mediated by altered melanocortin signaling. On the other hand, some children with  
 6 *SIM1* mutations have neuro-behavioral disorders including autism spectrum and “Prader-  
 7 Willi-like” phenotype (Figure 2) [3, 12].

8 In mice, hyperphagia associated with *SIM1* deficit can be improved by the administration of  
 9 oxytocin, a neurotransmitter involved in the modulation of emotion (impaired oxytocinergic  
 10 signaling is also one possible mechanism implicated in the obesity) [58].

## 11 2.8. Other types of non-syndromic genetic obesity

12 Mutations of the *BDNF* (*brain-derived neurotrophic factor*, OMIM \*113505, mapped at 11p14.1)  
 13 and its receptor *TrkB* (*tyrosin kinase B receptor*, OMIM \*600456, mapped at 9q21.33) are rare  
 14 causes of monogenic obesity acting downstream signal cascade of MC4-R and blocking  
 15 translation [59].

16 *BDNF*'s role in energy homeostasis emerged in the 1990s with the observation that intracere-  
 17 broventricular *BDNF* administration suppresses appetite and induces weight loss in ro-  
 18 dents, and *Bdnf* heterozygous knockout mice exhibit hyperphagia and obesity [60]. Complete  
 19 lack of *BDNF* during embryologic development is perinatally lethal, but haploinsufficiency  
 20 for *BDNF* or inactivating mutations of the *BDNF* receptor was associated with increased ad-  
 21 libitum food intake, severe early-onset obesity, hyperactivity, and cognitive impairment [60,  
 22 61]. Multiple genome-wide association studies of obesity in children and adults of different  
 23 racial and ethnic populations have found associations for single-nucleotide polymorphisms  
 24 (SNPs) at the *BDNF* locus and BMI, in particular for *G196A* variant (*rs6265*), which leads to a  
 25 valine to methionine substitution at the 66th amino acid position (*Val66Met*) of the N-terminal  
 26 prodomain of pro-*BDNF*. Furthermore, modifying factors—particularly sex, lifestyle behav-  
 27 iors, and psychotropic medication use—appear to be important confounders for the associa-  
 28 tion between *rs6265* and BMI [60–62]. In addition, the minor C allele of intronic *rs12291063*  
 29 SNP was associated with lower *BDNF* expression and higher BMI [63].

30 *NTRK2* (*TrkB*) mutation (which interferes with receptor autophosphorylation) causes the same  
 31 symptoms of *BDNF* deficiency such as hyperphagia, obesity, impaired nociception, and  
 32 intellectual disability [64, 65]. Recently, a *de novo* mutations in *TrkB* was found in a boy with  
 33 severe obesity and impairment in learning, memory and nociception, and in a girl with  
 34 hyperphagia and severe obesity [66].

35 Another cause of non-syndromic monogenic obesity is due to a gene mutation of *CART*  
 36 (*cocaine- and amphetamine-regulated transcript*, OMIM \*602606), mapped at 5q13.2. *CART* is an  
 37 anorexigenic peptide produced by specific hypothalamic neurons in response to the stimulus  
 38 of leptin. It would appear to mediate the termogenetic effects and energy expenditures  
 39 characteristic of leptin. It has been shown that mutations in the *CART* gene are associated with

- 1 reduced levels of the peptide encoded by it. Adolescents carrying a missense mutation in the  
 2 *CART* gene exhibit severe obesity associated with anxiety and depression [11, 67, 68].
- 3 Other recent forms of monogenic obesity, still being defined, are associated with *MRAP2*  
 4 (*melanocortin 2 receptor accessory protein 2*, OMIM \*615410, mapped at 6q14.2) mutation  
 5 encoding a *MC4-R* co-receptor, and with *KSR2* (*Kinase suppressor of Ras 2*, OMIM \*610737,  
 6 mapped at 12q24.22-q24.23) mutation, a protein involved in intracellular signal with a role in  
 7 energy homeostasis [69–72].

### 8 3. Syndromic obesity

- 9 To date have been identified syndromic forms (e.g., Prader-Willi Syndrome) in which obesity  
 10 can be associated with other signs and symptoms, such as intellectual disability, dysmorphic  
 11 features and unusual behaviors.
- 12 In these syndromes, obesity can be caused by hyperphagia because are involved genes related  
 13 to central nervous system appetite control centers.
- 14 Recently, the genetic bases for some of these syndromes have been elucidated and are begin-  
 15 ning to provide insights into the pathogenesis of the derangements of energy homeostasis.
- 16 **Table 2** reports the main syndromic forms of obesity. High-throughput technologies, and in  
 17 particular copy number variants (CNVs) detection, are likely to result in the identification and  
 18 recognition of multiple new syndromes where obesity and developmental delay are closely  
 19 associated [12].

Syndrome	Clinical features in addition to obesity	Prevalence	Genetic
<b>Bardet-Biedl</b>	Mental retardation, retinal dystrophy or pigmentary retinopathy, dysmorphic extremities, hypogonadism, kidney anomalies	1/125,000 to 1/175,000 births	BBS1 (11q13); BBS2 (16q12.2); BBS3 ( <i>ARL6</i> , 3q11); BBS4 (15q24.1); BBS5 (2q31.1); BBS6 ( <i>MKKS</i> , 20p12); BBS7 (4q27); BBS8 ( <i>TTC8</i> , 14q31); BBS9 ( <i>PTHB1</i> , 7p14); BBS10 ( <i>C12ORF58</i> , 12q21.2); BBS 11 ( <i>TRIM32</i> , 9q33.1); BBS12 ( <i>FLJ35630</i> , 4q27); BBS13 ( <i>MKS1</i> , 17q23); BBS14 ( <i>CEP290</i> , 12q21.3); BBS15 ( <i>WDPCP</i> , 2p15); BBS16 ( <i>SDCCAG8</i> , 1q43); BBS17 ( <i>LZTFL1</i> , 3p21); BBS18 ( <i>BBIP1</i> , 10q25); BBS19 ( <i>IFT27</i> , 22q12)
<b>Prader-Willi</b>	Neonatal hypotonia, mental retardation, hyperphagia, facial dysmorpby,	1/25,000 births	Lack of the paternal segment 15q11-q13 (microdeletion, maternal disomy, imprinting)

Syndrome	Clinical features in addition to obesity	Prevalence	Genetic
	hypogonadotropic hypogonadism, short stature		defect or reciprocal translocation)
<b>Cohen</b>	Retinal dystrophy, prominent central incisors, dysmorphic extremities, microcephaly, cyclic neutropenia	Diagnosed in fewer than 1000 patients worldwide	Autosomal recessive <i>COH1</i> gene (chr 8q22-q23)
<b>Alström</b>	Retinal dystrophy, neurosensory deafness, diabetes, dilated cardiomyopathy	Diagnosed in about 950 patients worldwide	Autosomal recessive <i>ALMS1</i> gene (chr 2p13-p14)
<b>X fragile</b>	Mental retardation, hyperkinetic behavior, macroorchidism, large ears, prominent jaw	1/2500 births	X-linked <i>FMR1</i> gene (Xq27.3)
<b>Borjeson-Forsman-Lehmann</b>	Mental retardation, hypotonia, hypogonadism, facial dysmorphism with large ears, epilepsy	Approximately 50 reported patients	X-linked <i>PHF6</i> gene (Xq26-q27)
<b>Albright hereditary osteodystrophy</b>	Short stature, skeletal defects, facial dysmorphism, endocrine anomalies	1/1,000,000 births	Autosomal dominant <i>GNAS1</i> gene (20q13.2)
<b>Ulnar-mammary</b>	Upper limb malformation (from hypoplasia of the terminal phalanx of the fifth digit to aplasia of hand and upper limbs on the ulnar side), abnormal development of mammary glands and nipples, teeth, genitalia, and of apocrine glands		Autosomal dominant <i>TBX3</i> gene (12q24.21)
<b>Simpson-Golabi-Behmel</b>	Multiple congenital abnormalities, pre-/post-natal overgrowth, distinctive craniofacial features, macrocephaly, and organomegaly.		X-linked <i>GPC4</i> gene (Xq26)
<b>MEHMO syndrome</b>	Mental retardation, epileptic seizures, hypogonitalism, microcephaly and obesity	Approximately <1/1,000,000 births	X-linked locus MEHMO (Xp22.13-p21.1)
<b>1p36 deletion syndrome</b>	Delayed growth, malformations, moderate to severe intellectual disability, live births seizures, hearing and vision impairment, and certain particular facial features.	1/5000 to 1/10,000	Autosomal dominant microdeletion of 1p36
<b>16p11.2 deletion syndrome</b>	Developmental delay, intellectual disability, autism spectrum disorders, impaired communication, socialization skills	Approximately 3/10,000 births	Autosomal dominant microdeletion of 16p11.2
<b>ACPI, TMEM18, MYT1L deletion</b>	Hyperphagia, intellectual deficiency, severe behavioral difficulties	Approximately 13 reported patients	Paternal deletion encompassing the <i>ACPI</i> , <i>TMEM18</i> , <i>MYT1L</i> genes (2p25)

1 Table 2. Main forms of syndromic obesity.

### 1 3.1. Developmental obesity syndromes involving ciliary dysfunction

2 Some genes linked to obesity have been associated with the function or formation of primary  
3 cilia, subcellular organelles, which serve a sensory function for most cell types. The ciliopathies  
4 form a class of genetic disease whose etiology lies with primary ciliary dysfunction. Some  
5 peculiar features can be found, such as retinal degeneration. This feature is of particular interest  
6 for its clinical relevance, rarity, and diagnostic power. Between these groups of diseases, we  
7 can include the Bardet-Biedl syndrome (BBS) and Alström syndrome (ALMS).

8 BBS has become a model ciliopathy because it became the first disease whose etiology lay in  
9 primary ciliary disorder [73]. It is a rare autosomal recessive genetic disorder with severe  
10 multiorgan impairment [74]. Its frequency in Europe and North America falls below 1:100,000  
11 [75]. The disease symptoms may significantly vary between the patients; therefore, the  
12 diagnosis relies on the number of primary and secondary features of BBS [74]. Multiple articles  
13 summarize the data on frequencies of various symptoms in BBS patients [75, 76]. However, it  
14 is very important to realize that almost all clinical studies analyzed patients of various ages.  
15 Many individuals with BBS look virtually healthy at birth unless they were born with a  
16 polydactyly. Other symptoms of BBS tend to gradually emerge during or after the first decade  
17 of life; thus, patients diagnosed at early childhood tend to have fewer clinical features of the  
18 disease [74]. There are six primary features of BBS, that is, rod-cone dystrophy, polydactyly,  
19 obesity, genital abnormalities, renal defects, and learning difficulties. Secondary features  
20 include developmental delay, speech deficit, brachydactyly or syndactyly, dental defects,  
21 ataxia or poor coordination, olfactory deficit, diabetes mellitus, and congenital heart disease  
22 [75]. Some authors also mention hypertension, liver abnormalities, bronchial asthma, otitis,  
23 rhinitis, craniofacial dysmorphism, etc. [75–78].

24 However, the phenotype can be different: generally, obesity occurs early in life of patients  
25 affected by BBS, but the literature shows that 52% of post-pubertal BBS patients are obese [79].  
26 It is recommended to assign BBS diagnosis to patients bearing at least 4 out of 6 primary  
27 features of the disease. If only three primary features are detected, two secondary features are  
28 required to confirm the presence of BBS.

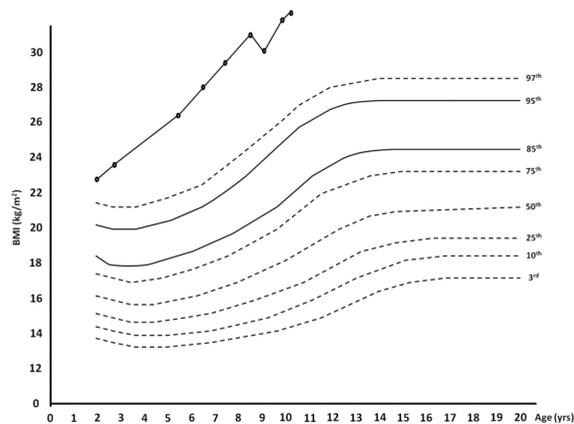
29 These criteria describe BBS mainly as a clinical entity; they do not fully account to the existence  
30 of patients with attenuated forms of the disease as well as to possible gene-specific manifesta-  
31 tions of BBS [80, 81].

32 At least 20 BBS genes have already been identified, and all of them are involved in primary  
33 cilia functioning. Genetic diagnosis of BBS is complicated due to lack of gene-specific disease  
34 symptoms; however, it is gradually becoming more accessible with the invention of multigene  
35 sequencing technologies [74].

36 The first five BBS loci were identified via linkage analysis of large BBS pedigrees [82–86] with  
37 corresponding genes cloned some years later [87–92]. The first gene assigned to BBS was *MKKS*  
38 (*MKS*; OMIM \*604896) already known to induce McKusick-Kaufman syndrome; given that it  
39 did not belong to previously identified BBS loci, it was named *BBS6*. At present, there are  
40 already 21 known BBS genes (*BBS1–BBS20* and *NPHP1*), and their number is likely to increase  
41 due to the invention of exome sequencing and analysis of previously unstudied populations

1 [74]. Strikingly, all BBS genes participate in cilia functioning, being a part of BBSome (*BBS1*  
 2 [11q13.2; OMIM \*209901], *BBS2* [16q13; OMIM \*606151], *BBS4* [15q24.1; OMIM \*600374], *BBS5*  
 3 [2q31.1; OMIM \*603650], *BBS7* [4q27; OMIM \*607590], *BBS8* [14q31.3; OMIM \*608132], *BBS9*  
 4 [7p14.3; OMIM \*607968], *BBS17* [3p21.31; OMIM \*606568], and *BBS18* [10q25.2; OMIM  
 5 \*613605]); chaperonin complex (*BBS6* [20p12.2; OMIM \*604896], *BBS10* [12q21.2; OMIM  
 6 \*610148], and *BBS12* [4q27; OMIM \*610683]); basal body (*BBS13* [17q22; OMIM \*609883], *BBS14*  
 7 [12q21.32; OMIM \*610142], *BBS15* [2p15; OMIM \*613580], and *BBS16* [1q43-q44; OMIM  
 8 \*613524]) or having some related biological function (*BBS3* [3q11.2; OMIM \*608845], *BBS11*  
 9 [9q33.1; OMIM \*602290], *BBS19* [22q12.3; OMIM \*615870], *BBS20*, and *NPHP1* [2q13; OMIM  
 10 \*607100]) [74].

11 Many of these genes appear to affect proteins localized to the basal body, a key element of the  
 12 monocilium thought to be important for intercellular sensing in mammalian cells including  
 13 neurons [73]. The literature shows that ciliary function is associated with leptin signaling [93].  
 14 As evidenced by some studies in mice, hyperphagia and obesity are caused by conditional  
 15 post-natal knockout of proteins involved in intraflagellar transport [94], but they occur also  
 16 when the loss of cilia affects the neurons, in particular POMC neurons [94].



17

18 **Figure 3.** BMI growth chart in a girl with Alström syndrome.

19 Alström syndrome (ALMS; OMIM #203800) is a rare genetic disorder that has been included  
 20 in the ciliopathies group, in the last few years [95].

21 The estimated prevalence for ALMS is one to nine cases per 1,000,000 individuals with nearly  
 22 900 cases described worldwide to date. Symptoms first appear in infancy and progressive  
 23 development of multi-organ pathology lead to a reduced life expectancy. Variability in age of

1 onset and severity of clinical symptoms, even within families, are likely due to genetic  
2 background [95].

3 Children typically develop obesity by age 5 years, associated with hyperinsulinemia, chronic  
4 hyperglycemia and neurosensory deficits (**Figure 3**) [6]. Children affected by ALMS, like  
5 children with BBS, have visual impairment and deafness that occurs early in life but its  
6 incidence is higher in these patients as well as NIDDM, found in up to 70% of individuals by  
7 age 20 years [96, 97].

8 In addition, ALMS is also associated with cardiomyopathy, renal anomalies and endocrino-  
9 pathies such as hypertriglyceridemia, pubertal delay, and hyperandrogenism and growth  
10 hormone deficiency [97].

11 Until now, disease-causing mutations in the *ALMS1* (2p13.1; OMIM \*606844) gene have been  
12 involved in this disorder.

13 The diagnosis is based on the phenotype of the patient, and it is confirmed when two muta-  
14 tions in *ALMS1* gene are identifies through molecular analysis.

15 However, it is difficult to diagnose early ALMS first of all because symptoms arise gradually  
16 and secondly because the phenotypes overlap, in particular with BBS in the case of ALMS [98].

17 In recent times, thanks to the discovery of new genetic tools, in particular next-generation  
18 sequencing (NGS) technology, a large number of patients have been diagnosed. The advent of  
19 these new techniques allows early diagnosis also in those patients who do not have a charac-  
20 teristic phenotype, thus preventing long-term complications that can be caused by a delay in  
21 diagnosis [99].

22 Today, the most used genetic techniques are whole-exome sequencing (WES) and whole-  
23 genome sequencing, thanks to their low cost. However, they are also important because they  
24 allow to exclude the mutations in other genes [99, 100].

25 The WES is a rapid and easier technique because it analyzes all coding regions in the genome  
26 [100]. Thanks to it, in fact, mutations in *ALMS1* gene have been identified in individuals, whose  
27 phenotype did not seem to be typical of ALMS; therefore, it is fundamental to identifying  
28 pathogenic mutations in compound heterozygous state in *ALMS1* gene, overcoming also  
29 limitation of genetic panels in patient suffering from familial dilated cardiomyopathy and  
30 severe heart failure [101].

31 In fact, as reported in literature, the association of WES and a previous linkage analysis has  
32 allowed to identify the pathogenic mutations in *ALMS1* gene in a consanguineous Turkish  
33 family with severe dilated cardiomyopathy although it did not present the typical phenotype  
34 of ALMS [102].

35 Moreover, these mutations have been shown also in consanguineous Leber congenital  
36 amaurosis families through homozygosity mapping followed by WES [103].

37 As evidenced by these studies, the simultaneous use of different genetic techniques is funda-  
38 mental both in the case of consanguineous families that in patients without the typical ALMS  
39 phenotype [95].

1 For management of the disease and to identify an accurate treatment, it is important for both  
 2 the present of typical clinical features that an appropriate genetic diagnosis, which may be  
 3 carried out by NGS techniques, thanks to its low cost compared with traditional polymerase  
 4 chain reaction and direct Sanger sequencing [103].

#### 5 **4. Imprinted genetic syndromes**

6 Prader-Willi syndrome (PWS, OMIM #176270) is a disorder caused by errors in genomic  
 7 imprinting, which generally occur during both male and female gametogenesis. In particular,  
 8 there is the loss of expression of paternal genes normally active and located in the chromosome  
 9 15q11-q13 region [104–108]. Conversely, a loss of expression of the preferentially maternally  
 10 expressed *UBE3A* (OMIM \*601623) gene in this region leads to Angelman syndrome (AS;  
 11 OMIM #105830), an entirely different clinical disorder that causes developmental disabilities  
 12 and neurological problems, such as difficulty speaking, balancing and walking, and, in some  
 13 cases, seizures [109, 110].

14 According to several studies, most individuals with PWS (about two-thirds) have a de novo  
 15 paternally inherited deletion of the chromosome 15q11-q13 region; about 25% of cases have  
 16 maternal disomy 15 (chromosome 15 is inherited from the mother) [111]; less than 3% of  
 17 patients have defects in the genomic imprinting center due to microdeletions or epimutations  
 18 [104, 106, 112, 113], while rearrangements of the 15q11-q13 region or chromosomal transloca-  
 19 tions are rare [104, 114].

20 However, this syndrome, whose prevalence is around of 1/10,000–1/30,000, is considered the  
 21 most common cause of syndromic obesity [115].

22 The cardinal features of PWS include infantile hypotonia, feeding difficulties due to a poor  
 23 suck and failure to thrive (FTT), followed in later infancy or early childhood by excessive  
 24 appetite with gradual development of obesity, short stature and/or decreased growth velocity  
 25 due to growth hormone (GH) deficiency, intellectual disabilities (average IQ of 65), behavioral  
 26 problems (e.g., temper tantrums, outburst and skin picking) and particular facial appearance  
 27 (e.g., a small upturned nose, narrow bifrontal diameter with almond-shaped eyes, down-  
 28 turned corners of the mouth with sticky salivary secretions and generally lighter skin, hair  
 29 and eye color than other family members) [105, 106]. Hypothalamic dysfunction has been  
 30 implicated in many manifestations of this syndrome including hyperphagia, temperature  
 31 instability, high pain threshold, sleep-disordered breathing and multiple endocrine abnor-  
 32 malities [105, 107, 108].

33 Initially, two nutritional phases have been described in children with PWS:

- 34 • phase 1: the individual often presents FTT; he exhibits hypotonia with difficult feeding;
- 35 • phase 2: the individual is hyperphagic, and this condition will lead to obesity [105, 108].

36 To date, instead, seven different nutritional phases (five main phases and sub-phases in phases  
 37 1 and 2) have been identified.

1 As following, focusing on nutrition, although in the early phases, the child has poor appetite,  
 2 the latter increases in phase 2b and leads progressively to hyperphagia, evident in phase 3  
 3 (Table 3).

Phases	Median ages	Clinical characteristics
0	Prenatal to birth	Decreased fetal movements and lower birth weight than sibs
1a	0–9 months	Hypotonia with difficulty feeding and decreased appetite. Needs assistance with feeding either through feeding tubes [nasal/oral gastric tube or gastrostomy tube] or orally with special, widened nipples
1b	9–25 months	Improved feeding and appetite and normal growth
2a	2.1–4.5 years	Weight increasing without appetite increase or excess calories. Will become obese if given the recommended daily allowance [RDA] for calories. Typically needs to be restricted to 60–80% of RDA to prevent obesity
2b	4.5–8 years	Weight and appetite are increased but can feel full
3	8 years to adulthood	Hyperphagic, rarely feels full
4	Adulthood	Appetite is no longer insatiable

4 Adapted with permission from Cassidy et al. [107].

5 **Table 3.** Clinical characteristics of the nutritional phases seen in Prader-Willi syndrome.

6 Analyzing the seven phases, we highlight the following:

- 7 • phase 0: the infant has growth restriction and decreased fetal movements;
- 8 • sub-phase 1a: the infant is hypotonic with difficulty feeding and with or without FTT;
- 9 • sub-phase 1b: the infant grows normally, and he improves appetite, also if weight gain is  
 10 normal;
- 11 • sub-phase 2a: the child has a weight gain although there is not an increased appetite or  
 12 caloric intake;
- 13 • sub-phase 2b: in addition to weight gain, there is an increased appetite;
- 14 • phase 3: the individual is hyperphagic; he seeks foods and presents the loss of sense of  
 15 satiety;
- 16 • phase 4: it is typical of adults, who have an insatiable appetite and are able to feel full [107].

17 As said previously, individuals with PWS present an appetite that gradually increases and  
 18 leads to obesity. In recent years, some studies have been conducted to understand the mech-  
 19 anisms controlling appetitive behavior, energy expenditure and body composition.

20 The central nervous system, in particular the hypothalamus that determines changes in energy  
 21 balance, is involved in these processes.

1 One of the determining factors for the development of obesity in these patients is ghrelin, a 28  
2 amino acid peptide produced in the stomach, that transmit satiety signal and whose level in  
3 obese PWS individuals is high [116, 117]. Circulating ghrelin levels are elevated in young  
4 children with PWS long before the onset of hyperphagia, especially during the early phase of  
5 poor appetite and feeding [118].

6 The literature reports that about 25% of the adults with PWS presents NIDDM (non-insulin-  
7 dependent diabetes mellitus) [119]; however, some studies show that in PWS, children fasting  
8 insulin concentrations and homeostasis model assessment insulin resistance index are lower  
9 than in obese control [120].

10 This syndrome, as mentioned, represents an human disorder related to genomic imprinting.  
11 Although the DNA sequence of the imprinted maternally and paternally inherited alleles is  
12 the same, multiple epigenetic factors (such as DNA methylation, histone modifications and  
13 chromatin conformation) ultimately will determine whether the imprinted allele is expressed  
14 or repressed [121, 122].

15 DNA methylation analysis is the most efficient way to start the genetic workup if PWS is  
16 suspected clinically, but it cannot distinguish the molecular class (i.e., deletion; uniparental  
17 disomy, UPD; or imprinting defect, ID). Therefore, once the diagnosis of PWS is established  
18 by DNA methylation analysis, determination of the molecular class is the next step.

19 There are different genetic testing used in PWS: CMA-SNP array or FISH (fluorescence in situ  
20 hybridization) for deletion of 15q11.2-q13, DNA polymorphism analysis for UPD or ID or  
21 testing with MS-MLPA analysis for an IC deletion, important for the diagnosis of both of these  
22 individuals who do not have sufficient features because they are too young than of those who  
23 do not exhibit the typical phenotype [107].

#### 24 **4.1. Cohen syndrome**

25 Cohen syndrome (CS) is an inherited disorder characterized by developmental delay, intel-  
26 lectual disability, microcephaly and hypotonia. Other features include progressive myopia,  
27 retinal dystrophy, hypermobility and distinctive facial features [6, 12]. Characteristic facial  
28 features include thick hair and eyebrows, long eyelashes, down-slanting and wave-shaped, a  
29 bulbous nasal tip, a smooth or shortened philtrum, and prominent upper central teeth [6, 12].  
30 Children with CS tend to manifest failure to thrive in infancy and early childhood but  
31 subsequently become significantly overweight in the late childhood and adolescence. The  
32 obesity tends to be truncal in nature [6, 12]. In contrast to PWS, appetite and food intake are  
33 not increased during this time period, and activity is not noticeably decreased. Among  
34 individuals with CS, the prevalence of short stature is approximately 65% and delayed puberty  
35 74%; clinical endocrinologic evaluations did not identify explanations for these findings [6, 12].

#### 36 **4.2. 1p36 deletion syndrome**

37 1p36 deletion syndrome is a disorder characterized by severe intellectual disability, hypotonia,  
38 heart defects, hearing impairment and typical craniofacial features. In fact, patients with this

1 syndrome show straight eyebrows, deeply set eyes, midface hypoplasia, broad and flat nasal  
2 root/bridge, long philtrum, pointed chin, large, late-closing anterior fontanel, microbrachyce-  
3 phaly, epicanthal folds and posteriorly rotated, low-set, abnormal ears. Other typical findings  
4 include brachy/camptodactyly and short feet. Developmental delay and intellectual disability  
5 of variable degree are present in all, and hypotonia in 95%. Seizures occur in 44–58% of affected  
6 individuals. Other findings include prenatal-onset growth deficiency, structural brain abnor-  
7 malities, congenital heart defects, vision problems, deafness, skeletal anomalies, abnormalities  
8 of the external genitalia and renal abnormalities. Obesity, which occurs as the consequence of  
9 hyperphagia, is also frequently observed in patients with the 1p36 deletion syndrome [123].  
10 In this recent report [124], 40% of patients had obesity and hypercholesterolemia, and 1 patient  
11 developed NIDDM. Some authors suggested candidate regions for hyperphagia and obesity,  
12 such as *PRKCZ*, that may be associated with obesity because this gene is involved in carbo-  
13 hydrate or lipid metabolism, or insulin signaling [123]. It is suggested that genetic or environ-  
14 mental factors more likely contribute to the development of obesity and DM. However, a subset  
15 of patients may become overweight and obese with hyperphagia and NIDDM [125]. Previous  
16 studies observed that obesity was found exclusively in female patients with 1p36 deletion who  
17 showed growth restriction during the fetal period [126]. Because patients with 1p36 deletion  
18 show hypotonia and hyperphagia with obesity and NIDDM, which are also characteristic  
19 features of patients with PWS, some patients with 1p36 deletion may be misdiagnosed as  
20 having PWS.

#### 21 4.3. 16p11.2 deletion syndrome

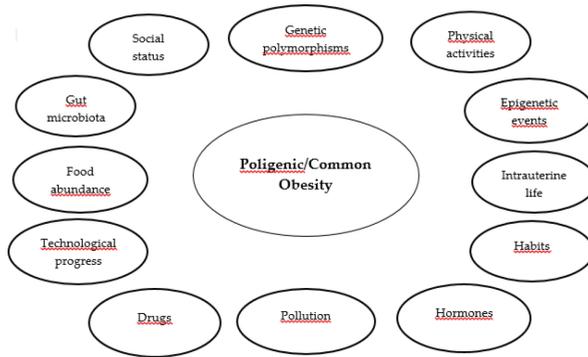
22 16p11.2 microdeletion syndrome is a chromosomal anomaly characterized by developmental  
23 and language delays, intellectual disability, social impairments represented by autism  
24 spectrum disorders, variable dysmorphisms and predisposition to obesity. In fact, in a  
25 screening cohort of patients with extreme obesity, enriched for patients with birth defects and/  
26 or neurocognitive deficiencies using method to detect copy number variations, recurrent, *de*  
27 *novo* deletions of 16p11.2 were identified in approximately 3% of cases. In these patients,  
28 durable weight loss has not been reported. So durable weight control is recommended  
29 although no data are available on the efficacy of early intervention in deletion carriers.  
30 However, impaired cognition may also result in abnormal eating behavior contributing to the  
31 obesity [127, 128]. Some data seem to hypothesize that this deletion may affect the neural  
32 circuitry involved in the energy balance. The early increase in head circumference seems to  
33 precede the onset of obesity [129]. The 16p11.2 deletion includes the *SH2B1* gene, an adaptor  
34 protein involved in leptin and insulin signaling which may be involved in the pathogenesis of  
35 the obesity and insulin resistance observed in this deletion [130].

36 Additionally, deficiencies of *SIM1* (single minded), *BDNF* (brain-derived neurotrophic  
37 factor) and *NTRK2* (neurotrophic tyrosine receptor kinase encoding the TrK protein, the  
38 receptor for BDNF) genes are associated with syndromic conditions involved in the function-  
39 ing of the hypothalamus downstream of MC4R-expressing neurons and leading severe  
40 hyperphagic obesity. For example, haploinsufficiency of *BDNF* has also been implicated in the

1 obesity occurring in a subset of patients with WAGR (Wilms tumor, aniridia, genitourinary  
 2 malformations and retardation) syndrome [62].

3 **4.4. Oligogenic obesity**

4 Oligogenic obesity or common obesity is the result of the set of behavioral, environmental and  
 5 genetic factors that may influence individual responses to diet and physical activity [131]  
 6 (Figure 4).



7

8 **Figure 4.** Gene–environment interactions in common obesity. Adapted with permission from Mutch and Clément  
 9 [131].

10 The obesogenic changes of our environment in recent decades, especially the unlimited supply  
 11 of cheap food with high palatability and high energy density, associated with genetic suscept-  
 12 ibility are the causes of the current obesity epidemic [132].

13 The recent rapid rise in prevalence of childhood obesity suggests that, probably, environmental  
 14 factors have a large impact on body weight in patients with common obesity although  
 15 individual responses to these environmental factors are influenced by genetic factors called  
 16 susceptibility genes [3].

17 Any of a group of alleles, at distinct gene loci that collectively control the inheritance of a  
 18 quantitative phenotype or modify the expression of a qualitative character, are termed  
 19 “polygenic” variants. A polygenic variant by itself has a small effect on the phenotype; only  
 20 in combination with other predisposing variants does a sizeable phenotypic effect arise.  
 21 Potentially, many such polygenic variants play a role in body weight regulation. It is estimated  
 22 that the total number of genes with a small effect most likely exceeds [133]. These genes are  
 23 involved in a variety of biological functions such as the regulation of food intake, energy  
 24 expenditure, carbohydrate and lipid metabolism and adipose tissue development [131].

1 Therefore, unlike monogenic obesity, many genes and chromosome regions contribute to  
2 common obesity phenotype.

3 Genome-wide association studies have identified genetic risks for obesity. In less than 4 years,  
4 52 genetic loci have been identified to be unequivocally associated with obesity-related traits  
5 [134]. However, these loci have only small effects on obesity susceptibility and explain just a  
6 fraction of the total variance. As such, their accuracy to predict obesity is poor and not  
7 competitive with the predictive ability of traditional risk factors such as parental and childhood  
8 obesity. The first convincing GWAS discovery for any obesity-related trait was made in 2007  
9 for BMI when the *FTO* locus was found to be associated with obesity-related traits and  
10 specifically with extreme and early-onset obesity in children and adolescents [134–136].  
11 Following the discovery of the *FTO* locus, one new locus near the *MC4R* was identified, a gene  
12 in which mutations are known to be the commonest cause of extreme childhood obesity. Also  
13 in recent years, other new BMI-associated loci were discovered such as near *TMEM18*  
14 (*transmembrane protein 18*, OMIM \*613220, 2p25.3), near *KCTD15* (*potassium channel tetramer-*  
15 *ization domain-containing protein 15*, OMIM \*615240, 19q13.11), near *GNPDA2* (*glucosamine-6-*  
16 *phosphate deaminase 2*, OMIM \*613222, 4p12), in *SH2B1* (*SH2B adaptor protein 1*, OMIM \*608937,  
17 16q11.2), in *MTCH2* (*mitochondrial carrier homolog 2*, OMIM \*613221, 11p11.2), near *NEGR1*  
18 (*neuronal growth regulator 1*, OMIM \*613173, 1p31.1), near *FAIM2* (*FAS apoptotic inhibitory*  
19 *molecule 2*, OMIM \*604306, 12q13.12), near *SEC16B* (*SEC16, homolog of S. cerevisiae B*, OMIM  
20 \*612855, 1q25.2), near *ETV5* (*ETS variant gene 5*, OMIM \*601600, 3q27.2) and in *BDNF* (*brain-*  
21 *derived neurotrophic factor*, OMIM \*113505, 11p14.1). Although for many of these loci, associa-  
22 tion with BMI has been observed in children and in adolescents [64, 137], and in populations  
23 of non-white origin, their replication has been less consistent than for the *FTO* and near-*MC4R*  
24 loci for relatively small sample size of the replication studies [134].

25 Furthermore, longitudinal studies have been published in recent years that have followed up  
26 children over time; these studies indicated that GWAS-discovered risk variants influence the  
27 development of obesity in part by accelerating weight gain during infancy and childhood [138–  
28 140], but the mechanisms by which this occurs are not yet fully elucidated. One of the mech-  
29 anisms involved may be the different sense of appetite, but the results of the studies are  
30 controversial [141, 142].

## 31 5. Epigenetics and obesity

32 Heritability estimates of BMI from twin studies range from 50 to 90% [143], so it plays a  
33 fundamental role in determining body weight. However, this latest figure appears in con-  
34 tradiction to the evidence of an epidemic increase in pediatric obesity over the last 20 years,  
35 time totally inadequate to record permanent changes in the genome. Only the reprogram-  
36 ming of gene expression through epigenetic modifications resulting from relevant environ-  
37 mental changes that have taken place mostly in the early periods of life may partially  
38 justify this phenomenon [11]. Epigenetic regulation of gene expression emerged in the last  
39 few years as a potential factor that might explain individual differences in obesity risk

1 [144]. Epigenetics can be defined as heritable changes that are mitotically stable (and poten-  
2 tially meiotically) and affect gene function but do not involve changes in the DNA se-  
3 quence [145].

4 Currently, there is a growing interest in the study of the relationship between genetic variation,  
5 epigenetic variation and disease simultaneously. The two main mechanisms that lead to  
6 epigenetic changes are DNA methylation, and the alterations to histone proteins that alter the  
7 likelihood that specific genes are transcribed [146, 147].

8 Interindividual variations in epigenetic changes like CpG methylation can potentially alter  
9 gene function and predispose to obesity. The variation in the degree of methylation, in fact, is  
10 able to modulate the expression of genes involved in controlling hypothalamic appetite [148].  
11 Using a genome-wide approach, obesity has been related to changes in DNA methylation  
12 status in peripheral blood leukocytes of lean and obese adolescents for two genes: in the  
13 *UBASH3A* (*ubiquitin-associated and SH3 domain-containing protein A*, OMIM \*605736, 21q22.3)  
14 gene, a CpG site showed higher methylation levels in obese cases, and one CpG site in the  
15 promoter region *TRIM3* (*tripartite motif-containing protein 3*, OMIM \*605493, 11p15.4) gene,  
16 showed lower methylation levels in the obese cases [149]. Also the obesity risk allele of *FTO*  
17 has been associated with higher methylation of sites within the first intron of the *FTO* gene,  
18 suggesting an interaction between genetic and epigenetic factors [150]. In addition, the obesity  
19 risk allele of *FTO* affects the methylation status of sites related to other genes (*KARS* [16q23.1;  
20 OMIM \*601421], *TERF2IP* [16q23.1; OMIM \*605061], *MSH1* [12q24.31; OMIM \*603328], *STON1*  
21 [2p16.3; OMIM \*605357] and *BCAS3* [OMIM \*607470]), showing that the *FTO* gene may  
22 influence the methylation level of other genes [151]. Finally, a recent work has demonstrated  
23 that hypermethylation of the *POMC* gene plays an important role in preparing to obesity by  
24 reducing the expression of the gene itself [148].

25 Epigenetic changes usually occur during prenatal development or the early post-natal  
26 period. Already *in utero*, in fact, there may be a switch of energy balance resulting from  
27 exposure to specific environmental factors, resulting in epigenetic changes that can affect the  
28 potential of the fat mass of offspring. For example in a recent work, the methylation status of  
29 CpG from five candidate genes in umbilical cord tissue DNA from healthy neonates was  
30 measured, and it was found that higher methylation levels within promoter region of *RXRRA*  
31 (*retinoid X receptor, alpha*, OMIM \*180245, 9q34.2) gene, measured at birth, were strongly  
32 correlated with greater adiposity in later childhood [152]. Maternal nutrition is a major factor  
33 leading to epigenetic changes. Thus, the levels of vitamins consumed in pregnancy such as  
34 folate, methionine and vitamin B12, which affect methylation, become very important [147].  
35 One study showed that prenatal exposure to malnutrition can determine abnormal DNA  
36 methylation resulting in epigenetic modifications that remain for the whole existence and that  
37 predispose to obesity and metabolic and cardiovascular risk in later life [153]. On the other  
38 hand also glycemic status during pregnancy is an important factor; in fact, hyperglycemia, as  
39 well as having a strong impact on the child's weight, can increase the risk of developing insulin  
40 resistance and obesity [147].

## 1 6. Steatosis and genetic of steatosis

2 Non-alcoholic fatty liver disease (NAFLD) actually represents the most frequent cause of  
3 chronic liver disease in industrialized countries in children and adolescents, as a direct  
4 consequence of the rise in childhood obesity [154]. Italian epidemiological data indicate that  
5 NAFLD affects approximately 3–10% of general pediatric population. This percentage  
6 increases up to >70%, with a male-to-female ratio of 2:1, in obese children [155]. NAFLD is  
7 defined by hepatic fat infiltration >5% hepatocytes, in the absence of other causes of liver  
8 pathology (such as daily alcohol utilization and either viral, autoimmune or drug-induced  
9 liver disease). It includes a spectrum of disease ranging from intrahepatic fat accumulation  
10 (steatosis) to various degrees of necrotic inflammation and fibrosis (non-alcoholic steatohepa-  
11 tatis [NASH]); simple steatosis has generally a benign course, but, rarely in children, NASH  
12 may progress to advanced and severe liver damage like cirrhosis and its complications  
13 (hepatocellular carcinoma and portal hypertension) [154, 156].

14 The pathogenesis of NAFLD appears to be multifactorial. The principal risk factor for fatty  
15 liver in childhood is obesity, but several other factors contribute to NAFLD development,  
16 including race/ethnicity, genetic factors, environmental exposures and alterations in the gut  
17 microbiome [157]. The dramatic rise in the prevalence of pediatric NAFLD is closely associated  
18 with the epidemic of obesity and metabolic syndrome; as in adulthood, pediatric NAFLD is  
19 associated with severe metabolic impairments such as insulin resistance, hypertension and  
20 abdominal obesity, determining an increased risk of developing type 2 diabetes mellitus, the  
21 metabolic syndrome and cardiovascular diseases [157, 158]. In addition, unhealthy food  
22 choices and the excessive fructose consumption in particular the fructose contained in the most  
23 common soda can promote the development of fatty liver [159].

24 The prevalence of hepatic steatosis varies among different ethnic groups. The ethnic group  
25 with the highest prevalence is the American Hispanic one (45%) followed by the Caucasian  
26 (33%) and the African-American (24%). The fatty liver prevalence in Europe, Australia and  
27 Middle East encompasses from 20 to 30%. In India, the fatty liver prevalence in urban popu-  
28 lations encompasses from 16 to 32%; but in rural India, where there are traditional diets and  
29 lifestyles, the prevalence is lower (about 9%); this evidence suggests that a sedentary lifestyle  
30 and globalization of Western diet could be associated with an increase in the fatty liver  
31 prevalence in developing nations. In all the ethnicity, NAFLD is more prevalent in boys than  
32 in girls with a male to female ratio of 2:1 [160, 161].

33 Regarding to genetic factors, one of the most important gene involved in determining hepatic  
34 steatosis is the *patatin-like phospholipase-containing domain 3* gene (*PNPLA3*). Genome-wide  
35 association studies and other pediatric studies have revealed that the *rs738409* (I148M) variant  
36 for *PNPLA3* confers susceptibility to NAFLD-promoting hepatic accumulation of triglycerides  
37 and cholesterol by inhibition of triglyceride hydrolysis [162]. In addition, a recent case-control  
38 study has demonstrated that the *rs9939609A* allele of the fat mass and obesity-associated gene  
39 (*FTO*) increases the risk of NAFLD [157].

40 Another gene that acts together with *PNPLA3* in determining hepatic steatosis is the glucoki-  
41 nase regulatory protein (*GCKR*) gene which encodes for the glucokinase regulatory protein

1 (GCKRP) that inhibits the glucokinase (GCK) activity competing with the glucose, substrate  
2 of GCK. It has been demonstrated that the GCKRP L466 variant encodes for a protein that  
3 indirectly increased GCK activity. This increase in GCK hepatic activity promotes hepatic  
4 glucose metabolism, raises the concentrations of malonyl coenzyme A, a substrate for de novo  
5 lipogenesis, and contributes in liver fat accumulation [160, 163]. In addition, a study conducted  
6 in Chinese children has shown that that the polymorphism *rs11235972* of the *uncoupling protein*  
7 *3 (UCP3)* gene is associated with the occurrence of NAFLD. *UCP3* is a mitochondrial protein  
8 with a highly selective expression in skeletal muscle, a major site of thermogenesis in humans.  
9 Genetic variants of *UCP3* have been associated with NIDDM and obesity [164].

10 *Apolipoprotein C3* gene (*APOC3*) *rs2854117* and *rs2854116* variants and *farnesyl-diphosphate*  
11 *farnesyltransferase 1 (FDFT1)* gene *rs2645424* variant have been also associated with NAFLD in  
12 adult [160]. Also in the recent years, genetic studies have demonstrated that single-nucleotide  
13 polymorphisms (SNPs) in genes involved in lipid metabolism (*Lipin 1, LPIN1*), oxidative  
14 stress (*superoxide dismutase 2, -SOD2*), insulin signaling (*insulin receptor substrate-1, IRS-1*) and  
15 fibrogenesis (*Kruppel-like factor 6, KLF6*) have been associated with a high risk for NAFLD  
16 development and progression [154]. Finally, a recent study evaluated the combined effect of  
17 four-polymorphisms genetic risk score in predicting NASH in NAFLD obese children with  
18 increased liver enzymes to help NASH diagnosis with the other non-invasive diagnostic tests  
19 [165].

20 In conclusion, obesity and fatty liver disease often go hand in hand even in the pediatric  
21 population, and both are pathologies related to genetic and environmental factors.

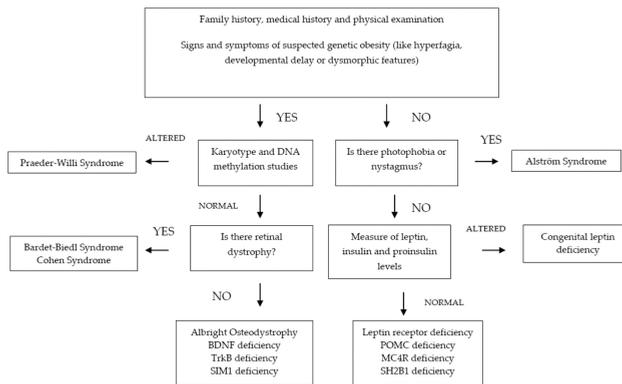
## 22 7. Genetic approach to obesity

23 Recognizing the monogenic syndromic and not syndromic obesity is really very important for  
24 at least two reasons: firstly, because it is hoped that, in the near future, making use of the results  
25 of other research in the field of obesity, obese patients can benefit from specific treatment (such  
26 as leptin administration and MC4R receptor agonists); secondly, because it is hoped that they  
27 will benefit from a multidisciplinary approach to the management of the symptoms, however,  
28 the clinical features of patients with genetic obesity are often very blurred, so that diagnosis  
29 can escape at first. **Figure 5** shows a diagnostic classification algorithm which can be useful in  
30 territorial pediatrics to suspect monogenic obesity and in the second and third levels in  
31 hospitals to orientate themselves in the execution of all the diagnostic tests in order to confirm  
32 the final diagnosis [12].

33 The genetic contribution to common obesity has been established initially through family, twin  
34 and adoption studies. Twin studies have shown a relatively high heritability ranging from 40  
35 to 77% [6]. Gene identification for the last 15 years has been based on two genetic epidemio-  
36 logical approaches (candidate gene and genome-wide linkage methods). Recently, genome-  
37 wide association studies have brought great information on obesity-related genes.

38 *Candidate-gene studies:* The design of the candidate gene approach is simple; candidate genes  
39 are genes that, according to their characteristics, can be considered causally related to the

1 disease. This method is based on the following resources: animal models using gene knockout  
 2 and transgenic approaches and cellular model systems showing their role in metabolic  
 3 pathways involved in glucose metabolism. There are two main types of candidates that are  
 4 generally considered in such studies: functional and positional. Functional candidates are  
 5 genes with products that are in some way involved in the pathogenesis of the disease.  
 6 Positional candidates are genes that are identified because they lie within genomic regions that  
 7 have been shown to be genetically important in linkage or association studies, or by the  
 8 detection of chromosomal translocations that disrupt the gene [2, 3]. The latest update of the  
 9 Human Obesity GeneMap reported 127 candidate genes for obesity-related traits. Results of  
 10 large-scale studies suggest that obesity is strongly associated with genetic variants in the *MC4R*  
 11 gene, *adrenergic β3 receptor (ADRB3)* gene, *PCSK1* gene, *BDNF* gene and *endocannabinoid receptor*  
 12 *1 (CNRI)* gene [16].



13

14 **Figure 5.** Diagnostic approach to genetic obesity. Adapted with permission from Farooqi and O’Rahilly [12].

15 *Genome-wide linkage studies:* Genome-wide linkage studies (GWLS) identify new, unforeseen  
 16 genetic variants associated with a disease or a feature of interest. They rely on kinship of study  
 17 participants and seek to identify chromosomal regions that tend to be co-inherited by indi-  
 18 viduals. The limit of genome-wide linkage studies is that they have a rather coarse resolution  
 19 and typically identify broad intervals that require follow-up genotyping to pinpoint the genes  
 20 that underlie the linkage signal [17]. The latest Human Obesity Gene Map update reported 253  
 21 loci from 61 genome-wide linkage scans, of which 15 loci have been replicated in at least three  
 22 studies [16].

23 *Genome-wide association studies:* Genome-wide association studies (GWAS) are used in genetic  
 24 research to look for associations between many (typically hundreds of thousands) specific  
 25 genetic variations (more commonly, single-nucleotide polymorphisms, SNP) and particular  
 26 diseases or traits. Genome-wide association studies have a higher resolution levels and are

1 able to narrow down the locus associated with greater accuracy, so this approach took place  
2 in the genome-wide linkage studies for common disease [3]. This new approach has found  
3 about 30 loci associated with obesity and high BMI. The strongest association is with FTO gene  
4 (the fat-mass and obesity-related gene) mutations. Also BDNF, SH2B1 e NEGR1 mutations are  
5 associated with obesity and support that obesity is a disorder of hypothalamic function [17].

6 Since the beginning of the genome-wide association study (GWAS) era in 2005, a number of  
7 large GWASs have been conducted on obesity-related traits in humans. A large meta-analysis  
8 from 46 studies conducted by the Genetic Investigation of Anthropometric Traits (GIANT)  
9 [166] consortium identified 32 SNPs robustly associated with adult BMI. The majority of these  
10 SNPs demonstrated directionally consistent effects in age- and sex-adjusted BMI in children  
11 and adolescents. However, even in combination, the 32 established SNPs explain <2% of the  
12 variation in BMI in either adults or children. The mismatch between the high heritability  
13 estimates from twin and other family studies (40–70%) and the small percentage of variation  
14 explained through GWAS (<2%) is called the problem of “missing heritability” [167, 168]. A  
15 portion of the missing heritability appears to be due to rare genetic variants and some non-  
16 additive genetic effects that are not found in analyses GWAS that showed only additional  
17 effects of common SNPs with minor allele frequencies (MAF) of >5%. Another part of the  
18 missing heritability can be explained by the fact that multiple additional common genetic  
19 mutations contribute to obesity, but they have a small effect that cannot be found by GWAS  
20 analyses [168].

21 New types of analyses, such as genome-wide complex trait analysis (GCTA), analysis of  
22 uncommon (MAF 0.5–1%) or rare (MAF 0.5%) variants and structural variants not detected by  
23 GWAS arrays, epigenetic analysis and gene–gene interactions (epistasis), are helping to fill that  
24 gap [167]. The purpose of the novel approach called genome-wide complex trait analysis  
25 (GCTA) is not to identify specific SNPs related to the target phenotype, but rather to estimate  
26 the total additive genetic effect of the common SNPs used on currently available DNA arrays  
27 [168].

28 The rare variant—common disease hypothesis—suggests that rare variants contribute  
29 significantly to complex traits. Probably, the obese phenotype is the consequence of additive  
30 effects and interactions among multiple alleles with varying magnitude of effect. Actually, we  
31 know that only 1% of the human genome is transcribed into mRNA and translated into  
32 proteins. An additional 0.5% is regulatory regions that control gene expression. Functions of  
33 the remaining 98.5% of the genome remain unknown. Rare variants might be identified by  
34 massive genotyping or deep sequencing in large families thanks to novel techniques that  
35 sequence millions of DNA strands in parallel and at low cost such as next-generation sequenc-  
36 ing techniques [169].

37 Copy number variants (CNVs) represent another source of the heritability that is missed by  
38 GWAS studies. Copy number variants (CNVs) are products of genomic rearrangements,  
39 resulting in deletions, duplications, inversions and translocations [167, 170]. The most  
40 established CNV in the obesity field is a large, rare chromosomal deletion at 16p11.2; this  
41 deletion includes a small number of genes, one of which is *SH2B1*, known to be involved in  
42 leptin and insulin signaling. The search for CNVs in the context of obesity has proved fruitful,

1 and it has become quite clear they play a role in the missing heritability that still needs to be  
2 explained for the disease [19, 170].

### 3 **8. Treatment options in patients with genetic obesity**

4 The use of pharmacologic treatment for obesity is recommended by the American Academy  
5 of Pediatrics (AAP) as an adjunct to lifestyle changes when obesity-related health risks exist  
6 and lifestyle changes have not been effective for an individual. In addition, the AAP recom-  
7 mends pharmacotherapy only for children with BMI  $\geq$ 99th percentile [171]. On the other hand,  
8 the Endocrine Society has suggested limiting pharmacotherapy to patients with a BMI over  
9 the 95th percentile who have failed diet and lifestyle intervention, or in limited cases with a  
10 BMI over the 85th percentile and severe comorbidities [147]. Overweight children should not  
11 be treated with pharmacotherapeutic agents unless significant, severe comorbidities persist  
12 despite intensive lifestyle modification. In these children, a strong family history of NIDDM  
13 or cardiovascular risk factors strengthens the case for pharmacotherapy [172].

14 There are currently only a few drugs approved for the treatment of obesity; such drugs belong  
15 to different pharmacologic categories with different mechanisms of action. A major class of  
16 medications used in weight treatment is appetite suppressants also called anorexigenic agents.  
17 These drugs increase hypothalamic levels of norepinephrine, dopamine and serotonin-promot-  
18 ing satiety and decreasing hunger [173]. Among the appetite suppressant drugs, sibutramine  
19 was used to treat obesity in children until recently. In 2010, sibutramine was withdrawn by the  
20 United States Federal Drug Administration (US FDA) and European Medicine Agency (EMA)  
21 for increased cardiovascular risk for individuals taking the medication [174]. As well, other  
22 drugs of the same class like ephedrine and fenfluramine were withdrawn from the market for  
23 their adverse effects [147]. With the withdrawal of sibutramine, orlistat and metformin are now  
24 the only available drugs for the treatment of pediatric obesity.

25 Orlistat, an inhibitor of pancreatic lipases, prevents the breakdown of triglycerides into  
26 absorbable fatty acids and monoglycerols. Thus, about one-third of the dietary intake,  
27 triglycerides is not absorbed. It reduces body weight, total cholesterol and LDL cholesterol,  
28 and the risk of NIDDM in adults with abnormal carbohydrate metabolism. In USA, orlistat is  
29 approved by the FDA in adolescents older than 12 years [175]. It is associated with a significant  
30 fall in BMI of 0.7 kg/m<sup>2</sup>, but treatment is associated with increased rates of side effects including  
31 abdominal discomfort, pain, steatorrhoea and decreased absorption of the fat-soluble vitamins  
32 A, D, E and K. So, it is important to take those fat-soluble vitamins supplementation 2-h  
33 distance from orlistat administration [147]. Side effects are usually mild to moderate and  
34 generally decrease in frequency with continued treatment; this decrease may result from  
35 patients learning to consume less dietary fat to avoid these side effects. Typically, doses of  
36 120 mg by mouth three times daily are needed for effectiveness [176, 177].

37 Although metformin has not been approved by the US FDA for the treatment of obesity, it may  
38 be effective as a weight loss agent in addition to its effects as a hypoglycemic agent. Its major  
39 site of action is the liver: the drug increases glucose uptake, decreases hepatic gluconeogenesis

- 1 and reduces hepatic glucose production; also, metformin inhibits lipogenesis and increases  
2 insulin sensitivity and may have an effect as an appetite suppressant. The major benefits of the  
3 medication are reduction of food intake, weight loss, visceral fat reduction, improvement of the  
4 lipid profile and of the carbohydrate intolerance [172, 175, 178]. A systematic assessed five  
5 randomized controlled trials all with follow-up of at least 6 months; compared to placebo,  
6 metformin reduced BMI by 1.42 kg/m<sup>2</sup> in obese children [179]. Patients treated with metformin  
7 report abdominal discomfort, which improves when the drug is taken with food. There is also  
8 a risk of vitamin B12 deficiency; therefore, a multivitamin is recommended. The risk of lactic  
9 acidosis has been observed in adults but not seen in pediatric patients [147].
- 10 Octreotide, a somatostatin analogue, has been investigated as a treatment for hypothalamic  
11 obesity. It binds receptors on the beta cells of the pancreas and inhibits insulin release [147]. A  
12 study comparing octreotide with placebo has demonstrated statistically significant weight loss  
13 and statistically significant mean decreases in BMI among those treated with octreotide for 6  
14 months [180]. Octreotide works better in patients with insulin hypersecretion and insulin  
15 resistance. A study has demonstrated that greater weight loss correlated with a greater degree  
16 of insulin hypersecretion [181]. The high cost of the drug and the various side effects (gastro-  
17 intestinal problems, gallstones, GH and TSH suppression, cardiac dysfunction) limit currently  
18 use [175].
- 19 In the case of monogenic obesity, subcutaneous injection of recombinant human leptin in  
20 children and adults with *LEP* mutations resulted in weight loss, mainly of fat mass, with a  
21 major effect on reducing food and hyperphagia, induction of puberty (even in adults) and  
22 improvement in T-cell responsiveness [24, 25, 27, 182]. Leptin treatment works in patients with  
23 leptin deficiency or with bioinactive leptin, but on the other hand, leptin treatment is useless  
24 in *LEPR*-deficient subjects, because the receptor mutations make it inactive [24, 183].
- 25 In the case of children with PWS, GH therapy can improve growth, body composition, muscle  
26 thickness, physical strength and agility, motor performance, fat utilization, and lipid metabo-  
27 lism [184–186]. The best response to GH in PWS patients is observed in the first 12 months of  
28 treatment. Although early treatment is important for the improvement in body composition,  
29 generally, in practice, it is possible to start treatment only after 2 years of age. Treatment can  
30 be started in a dose of 0.034 mg/kg/day (0.24 mg/kg/week) in infants, and toddlers and IGF-1  
31 and IGFBP-3 levels are used to specify the dose of GH therapy. Benefits of continuing GH  
32 therapy in adulthood remain unclear although an improvement has been observed in body  
33 composition and cognitive functions in patients who received treatment only in adulthood.  
34 Contraindications for GH therapy in PWS patients are severe obesity, uncontrolled diabetes  
35 mellitus, untreated severe OSA, active cancer and psychosis [108].
- 36 A number of the PWS features, such as hyperphagia, obesity and behavioral anomalies, may  
37 be due to consequent hypothalamic hyposecretion of oxytocin for the reduction of paraven-  
38 tricular nucleus neurons. A few studies have investigated the capacity of exogenous oxytocin  
39 to improve these PWS features, but other research is necessary [183].
- 40 For *MC4R*-deficient obese patients, currently, there are no specific treatments. Different *MC4R*  
41 agonists were studied in vivo in animal and human studies, and almost all studies are currently

1 in the preclinical phase. These pharmacological MC4R agonists can restore normal activity in  
2 mutated receptors, and in obese animal, models cause decreased food intake, increased total  
3 energy expenditure, weight loss and weight-independent improvement of insulin sensitivity  
4 after 8 weeks of treatment [43, 187].

5 Finally, most recent studies on the treatment of obesity have focused on the potential role of  
6 plants used for obesity and its metabolic disorders treatments, exerting a positive effect on  
7 lipid and glucose metabolism, and anti-inflammatory activity [188]. For example, green tea  
8 disclosed anti-obesity effects in both *in vitro* and *in vivo*, decreasing adipose tissue through the  
9 reduction of adipocytes differentiation and proliferation, showing a positive effect in lipid  
10 profile, and lipid and carbohydrates metabolisms, and anti-inflammatory activity [188].

11 However, in literature, the anti-obesity properties and the mechanisms of action of some plants  
12 such as *Camellia sinensis*, *Hibiscus sabdariffa*, *Hypericum perforatum*, *Persea americana*, *Phaseolus*  
13 *vulgaris*, *Capsicum annuum*, *Rosmarinus officinalis*, *Ilex paraguariensis*, *Citrus paradisi*, *Citrus*  
14 *limon*, *Punica granatum*, *Aloe vera*, *Taraxacum officinale* and *Arachis hypogea* have been described  
15 [189]. However, polysaccharide macromolecules slowing the rate of carbohydrate and fat  
16 absorption have been resulted help reduce insulinemic peaks, enhancing  $\beta$ -cell function and  
17 potentially restoring the insulin secretory reserve in patients with IGT or NIDDM and genetic  
18 obesity history [189].

19 Another possible therapy for childhood obesity is bariatric surgery. There are 3 types of  
20 bariatric procedures: malabsorptive, restrictive and combination procedures. The first proce-  
21 dures are the jejunioileal bypass and the biliopancreatic diversion with duodenal switch that  
22 manage to lose weight by reducing nutrient absorption through the gut anatomical rearrange-  
23 ments; however, these procedures are not approved in children for their high morbidity and  
24 mortality. The Roux-en-Y gastric bypass (RYGB) is a combination procedure; it has become the  
25 most commonly performed bariatric surgical procedure, and it involves a reduction of stomach  
26 size and the reduction of intestinal absorptive capacity via the creation of a gastrojeunal  
27 anastomosis [171, 172, 190]. Laparoscopic adjustable gastric banding (LAGB) is a wholly  
28 restrictive procedure, and it has been used more recently. This bariatric procedure is to place  
29 a balloon around the esophagogastric junction and inflate it with saline until you get the  
30 desired effect of the stomach size reduction. This procedure is recommended in children  
31 because it is reversible and does not create permanent intestinal rearrangements [171, 172,  
32 191]. Laparoscopic sleeve gastrectomy (LSG) is a new and attractive option for young patients.  
33 It is a new restrictive procedure without the malabsorptive component present in other  
34 bariatric procedures. This technique involves the removal of a large portion of the stomach  
35 through a vertical resection, and the remaining stomach has a volume drastically reduced, with  
36 a capacity of around 100/150 ml. Weight loss outcomes in some study were similar between  
37 pediatric and adult patients at all time points, suggesting that LSG is similarly safe and effective  
38 in young and adult patients through at least 1 year of follow-up [192].

39 The criteria for access to bariatric surgery in childhood are very restrictive: BMI >35 kg/m<sup>2</sup> with  
40 severe comorbidities or >40 kg/m<sup>2</sup> with comorbidities, Tanner stage 4 or 5, to achieve at least  
41 95% of the growth estimate in the case of malabsorptive procedures, the ability to follow the  
42 post-operative diet and exercise, an adequate social support, ability to follow constantly

1 medical indications and treatment and appropriate treatment of psychological problems [190].  
2 Also it is recommended that bariatric surgery be done only in centers that can provide a  
3 multidisciplinary pre- and post-operative evaluation and psychological support both before  
4 and after the surgery [193].

5 Currently, data on bariatric surgery in children and adolescents with genetic obesity are limited  
6 and still controversial [183]. To date, bariatric surgery experience in treating children and  
7 adolescents with monogenic and syndromic forms of obesity is limited, and different bariatric  
8 procedures have been used with varying success [194]. Some studies have demonstrated the  
9 efficacy of bariatric surgery (in terms of weight loss and reduction of comorbidities such as  
10 obstructive sleep apnea, dyslipidemia, hypertension, diabetes mellitus and poor mobility) in  
11 patients with monogenic obesity (such as LEPR-deficient patients and patients with hetero-  
12 zygous *MC4R* mutations, but not in patients with homozygous *MC4R* mutation [195]) and  
13 syndromic obesity (such as PWS, BBS, Alström syndrome) but, due to the limited number of  
14 cases, the long-term efficacy and safety of bariatric surgery in genetic forms of obesity need  
15 further evaluation [183].

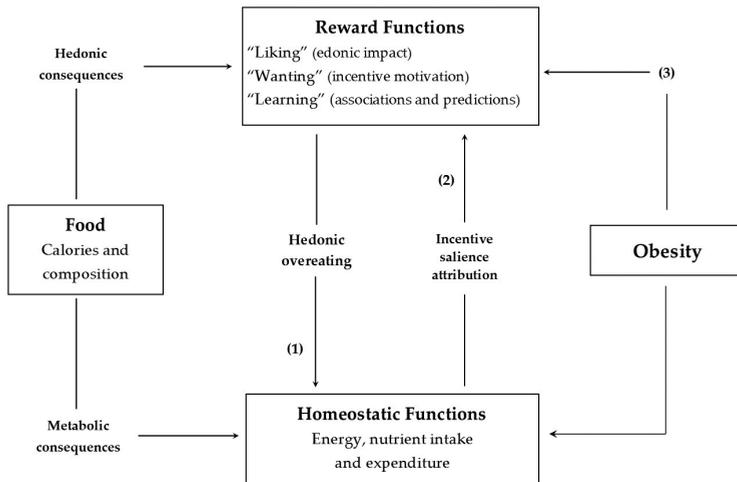
16 Even more in the early days are studies that try to correlate specific polymorphisms with  
17 response to bariatric surgery: For example, a study tried to find the presence of an association  
18 between several polymorphisms (including the *FTO* and *MC4R* genes) with post-operative  
19 weight loss [196]; another study found that a 15q26.1 locus is significantly associated with  
20 weight loss after Roux-en-Y gastric bypass surgery [197]. Thus, there is some evidence for the  
21 use of genomics to identify response to surgical procedures; the identification of genetic  
22 contributors could be useful to select those individuals who will obtain a greater benefit from  
23 a bariatric surgery. However, these results have yet to be confirmed.

## 24 **9. Hyperphagia: etiopathogenesis and treatment**

25 In the modern environment of plenty, obesity is favored by biological features that generally  
26 are advantageous in a restrictive environment, such as attraction to palatable and energy dense  
27 foods, slow satiety mechanisms and high metabolic efficiency [198].

28 The control of food intake and energy expenditure consists of a complex network of neural  
29 and hormonal systems that involving many genes [199]: in particular, the informations are  
30 collected at the peripheral level (intestine, stomach, adipose tissue); then, they are processed  
31 at the hypothalamic level and, finally, generate behavioral, endocrine and autonomic output  
32 [198].

33 In particular, much larger portions of the nervous system of animals and humans, including  
34 cortex, basal ganglia, and the limbic system, are concerned with the procurement of food as a  
35 basic and evolutionarily conserved survival mechanism to defend body weight [200]. These  
36 systems are directly and primarily involved in the interactions of the modern environment  
37 and lifestyle with the human body [198]. By focusing on the neural reward systems and the  
38 interaction between reward and homeostatic functions, it is possible to infer that the disturb-  
39 ance of this relationship determines obesity (**Figure 6**).



1



2 **Figure 6.** Relationship between metabolic and hedonic controls of food intake and energy balance. Adapted with per-  
 3 mission from Berthoud et al. [196].

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4 This process can generate hedonic and metabolic consequences, which are independent from  
 5 each other: in particular, the hedonic consequences are regulated by reward functions while  
 6 the metabolic consequences of food (defined in terms of their input of energy and their effects  
 7 on body composition, particularly increased fat accretion as in obesity) are regulated by  
 8 homeostatic functions.

9 The alteration of reward functions may be a cause (i.e., excessive caloric intake modulated by  
 10 hedonic value of food (1)) and/or a consequence (induced by obese state (3)) of obesity [198].

11 As schematically depicted in **Figure 6**, several potential interactions exist between food reward  
 12 and obesity.

13 In particular, there are three fundamental mechanisms involved in the development of obesity,  
 14 which are not mutually exclusive, but a combination of all three is operative in most individ-  
 15 uals: excessive intake of palatable and energy dense foods, differences (genetic and other pre-  
 16 existent) in reward functions and increase of obese state consequently to alterations of reward  
 17 functions induced by obesity [198].

18 It is also important to realize that hyperphagia is not always necessary for obesity to develop,  
 19 as the macronutrient composition of food can independently favor fat deposition.

20 In this regard, there is the "*gluttony hypothesis*" emerged from several studies in animals: in  
 21 particular, although reward functions are not altered unlimited access to palatable food and

1 food cues leads to excessive caloric intake (hedonic overeating) and, consequently, to obesity  
2 (defined as diet-induced obesity) [198].

3 However, it is important to underline that not all individuals exposed to environment of plenty  
4 show an increased food intake and weight gain; this means that there are genetic and epigenetic  
5 pre-existing alterations that make some individuals more vulnerable to the increased availa-  
6 bility of palatable food and food cues [198].

7 One of the key questions is how the motivation to get a reward will translate into action. In  
8 most cases, the motivation for something comes from the pleasure that this has generated in  
9 the past, or in other words, to obtain what has been helpful. The dopamine signal seems to be  
10 a critical component in this process [198].

11 The limited information available suggests that repeated sucrose access can upregulate  
12 dopamine release [201] and dopamine transporter [200] and change dopamine D1 and D2  
13 receptor availability [201] in the nucleus accumbens.

14 As demonstrated by some observations, such pleasurable foods have a high potential for addiction  
15 for which the withdrawal from it can cause symptoms such as anxiety, stress, depression  
16 resulting behavior of relapse because of occurring neural and molecular changes. Therefore,  
17 it is critical for switching the cycle of addiction and the prevention of a further spiral of  
18 addiction [198].

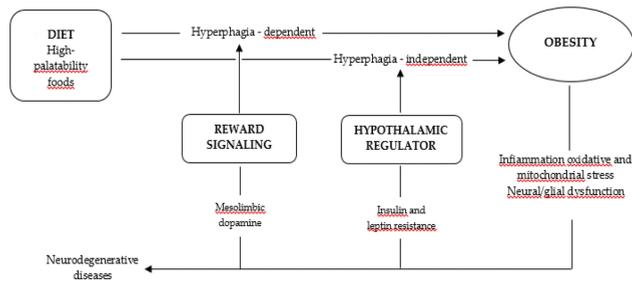
19 An issue on which to focus is that excessive caloric intake, as part of a disease, can gradually  
20 worsen: in fact at the beginning, there is overeating; then, the individual eats also in the absence  
21 of physiological hunger. Subsequently, there will be loss of control over eating (binge eating),  
22 and finally, hyperphagia defined as a hallmark of inherited disorders, in which obesity is  
23 present [203].

24 The term "hyperphagia" includes a series of conditions, such as binge eating disorder,  
25 hormonal imbalances such as glucocorticoid excess, leptin signaling abnormalities, syndromes  
26 associated with obesity and cognitive impairment (e.g., PWS) [203] and can be used in different  
27 situations: for example, to evaluate hunger and satiety through appropriate scales for patho-  
28 logical individuals compared to healthy individuals [203], to evaluate excessive caloric intake  
29 and the impact on body size and body composition in pathological individuals [203] or to  
30 evaluate preoccupation and psychological symptoms such as anxiety, stress due to hyperpha-  
31 gic behavior and the consequences that it determines (e.g., continuous search for food, night  
32 eating, ingestion of inedible food, theft of food, etc.) [203].

33 A person with hyperphagia has an obsessive and compulsive behavior towards food and often  
34 continues to eat for a long time, even if he/she feels full. This excessive nutriment can cause  
35 abdominal pain, guilt or drowsiness.

36 In particular, obesity is associated with dysregulated signaling systems, such as leptin and  
37 insulin resistance, as well as increased signaling through proinflammatory cytokines and  
38 pathways activated by oxidative and endoplasmic reticulum stress [204] (Figure 7).

AQ1



1

2 **Figure 7.** Secondary effects of obesity on reward circuitry and hypothalamic energy balance regulation. Adapted with  
 3 permission from Berthoud et al. [198].

- 4 As schematically depicted in **Figure 7**, obesity and, in turn, neurodegenerative diseases may  
 5 be caused by leptin resistance, central insulin and altered regulation of energy balance,  
 6 controlled by hypothalamus. About the latter, the literature shows that mitochondrial and  
 7 oxidative stress increase due to high-fat diets leading to neural/glial dysfunction and, conse-  
 8 quently, cytotoxic effects [198].
- 9 However, these toxic effects do not stop at the level of the hypothalamus but can also affect  
 10 brain areas involved in reward processing [198].

## 11 10. Nutritional and behavioral approach to genetic obesity

12 The approach to the child with genetic obesity is very complex considering that obesity is  
 13 associated with a number of complications that include the health of the child, and it must be  
 14 focused on the entire family. Awareness about the problem by all family members and, in  
 15 particular, changes in lifestyle and nutrition of the family are the most effective means both to  
 16 ensure the compliance to the treatment, the success of the therapy and the maintenance of the  
 17 long-term results.

18 The family, especially the parents, should be actively involved in the therapeutic program and  
 19 become protagonists. The targeted intervention with “individual” programs only for the child,  
 20 on the contrary, is often unsuccessful and frustrating for the child himself [205].

21 According to NICE guidelines on weight management in children dating from 2014 [206], it is  
 22 important to:

- 23 • coordinate the care of children and young people around their individual and family needs  
 24 [206];
- 25 • assess and intervene to improve child's health, considering his age and maturity. It is  
 26 important to set goals based on needs and preferences both of the child that of the whole  
 27 family [206];

- 1 • create an environment that promotes lifestyle changes within the family and in social  
2 settings. Parents (or carers) are responsible of these changes, especially if children are  
3 younger than 12 years old [206].
- 4 The initial assessment is important to collect data necessary for diagnosis and subsequent  
5 treatment. In particular, these informations regarding patient history (personal, familiar,  
6 healthy and social history), food/nutrition-related history (eating patterns, diet experience,  
7 physical activity, beliefs and attitudes about eating, etc.), anthropometric measures (current  
8 weight, weight history, etc.), biochemical data and medical tests (e.g., lipid profile, glucose  
9 profile, etc.); what the person has already tried and how successful this has been will be  
10 discussed, and what they learned from the experience; the person's readiness to adopt changes  
11 and their confidence in making changes will be assessed [206].
- 12 Multicomponent interventions are the treatment of choice. Weight management programs  
13 must include behavior change strategies to increase people's physical activity levels or decrease  
14 inactivity, improve eating behavior and the quality of the person's diet and reduce energy  
15 intake [206].
- 16 In particular, nutrition offered to obese children must also ensure the maintenance of adequate  
17 rhythms of growth and promote the maintenance of lean body mass (in particular of muscle  
18 mass), which represents the metabolically active compartment, and it is the large part of the  
19 total energy expenditure. Therefore, it must necessarily guarantee the macro- and micro-  
20 nutrients intake in relation to their age [205].
- 21 In overweight and obese children and young people, it is important a multidisciplinary  
22 intervention that includes dietary recommendations appropriate for age and complies with  
23 the principles for a healthy nutrition (in these patients, total energy intake should be below  
24 their energy expenditure) [206].
- 25 Dietary changes should be tailored to food preferences and allow for a flexible and individual  
26 approach to reducing calorie intake; it is important not to use unduly restrictive and nutri-  
27 tionally unbalanced diets because they are ineffective in the long term and can be harmful [206].
- 28 In these patients, it is also necessary that an intervention about physical activity is important  
29 not only for lose weight, but also for other health benefits, such as reduction risk of type 2  
30 diabetes or heart diseases [206].
- 31 Therefore, obese and overweight children must be encouraged to become more active and to  
32 reduce inactive behaviors, such as sitting and watching television, using a computer or playing  
33 video games and to do at least 60 min of moderate or greater intensity physical activity each  
34 day. The activity can be in 1 session or several sessions lasting 10 min or more [206].
- 35 It is important to make the choice of activity with the child and ensure that it is appropriate to  
36 the child's ability and confidence, giving children the opportunity and support to do more  
37 exercise in their daily lives (e.g., walking, cycling, using the stairs and active play) or to do  
38 more regular, structured physical activity (e.g., football, swimming or dancing) [206].
- 39 Children affected by genetic obesity (e.g., PWS) often eat more than necessary for anxiety,  
40 sadness, boredom: in this case, it is important not only to reduce the amount of foods but also

1 to search for reasons of suffering causing the overeating. It is important, therefore, to recon-  
2 struct the individual's self-esteem [206].

3 There are, however, barriers to parental involvement in the child's treatment: in some families,  
4 for cultural or psychological reasons, parents do not perceive their child as obese. In other  
5 families, parents may acknowledge that the child is obese but denies that this condition can  
6 have consequences.

7 Therefore, it is crucial to raise awareness among parents of the need to intervene, especially  
8 when behavioral changes are needed in the family [207].

9 Focusing on hyperphagic children, particularly those affected by Prader–Willi syndrome,  
10 parents must learn to celebrate each small goal, large or small, and to appreciate the acquisition  
11 of any new skill [208].

12 In these children, there are behavior changes that become more apparent and severe with age:  
13 in fact, they are concerned about food, hypersensitive, agitated, aggressive, impulsive, anxious.  
14 These behaviors are caused specially by their insatiable appetite that causes physical, emo-  
15 tional and social problems [209].

16 For these reasons, it is important to intervene to reduce stress not only for children, but also  
17 for the whole family.

18 However, to control the anxious behavior in children with PWS, the following information  
19 may be useful:

20 • having a regular daily routine, following appropriate food program;

21 • giving your child transitional warnings—that is, “after you finish that puzzle, it is time for  
22 bath” [209];

23 • preparing your child ahead of time if there is going to be a change in routine;

24 • re-directing your child to another activity;

25 • using positive reinforcement;

26 • speaking to your child in a calm, yet firm matter-of-fact tone [209].

27 In children with PWS, it is essential management food, based also on control food access, to  
28 ensure adequate nutrition, weight regulation and appropriate eating behaviors.

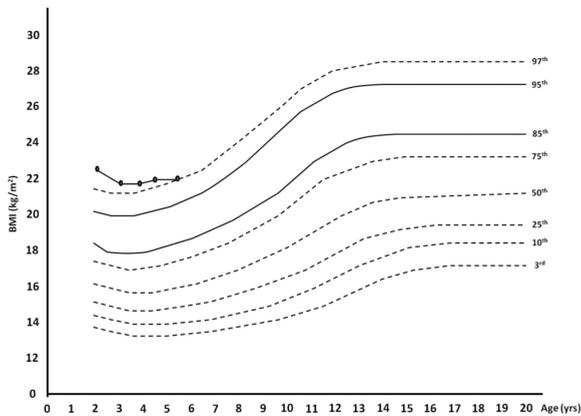
29 Crucial in this regard is the role of parents, who must support their children in these changes  
30 by adopting appropriate strategies.

31 However, each family will find the best way for them and for the specific need of their child.

32 First of all, it is important to follow an adequate food program that helps parents to monitor  
33 their food intake and reassures the child that the food will always be available: therefore, it  
34 represents the beginning for him to acquire the habit of eating healthy so that food can be  
35 controlled and could become a part of his daily routine [209].

1 This program is based on three main meals (breakfast, lunch, and dinner) and two or three  
 2 snacks (mid-morning snack, afternoon snack, and perhaps evening snack) [209]. It is funda-  
 3 mental to respect scheduled times (food must be given every 2–3 h), avoiding giving food  
 4 outside mealtimes. Whenever possible, all family members should eat at the same time and  
 5 others should not eat in front of the child when it is not their scheduled meal/snack time [209].  
 6 Portion control is another adequate strategy: it must not be excessive, but appropriate for the  
 7 child's age to ensure adequate growth [209].  
 8 However, food must be healthy considering that in children with PWS, calorie needs are lower  
 9 due to reduced metabolism. Food must be given only by parents/caregivers and served on the  
 10 plate prior to being eaten, avoiding other platters/bowls of food visible on the table and to  
 11 share or offer them other food [209].  
 12 At the end of the meal, it is important to remove the empty plate from the table and encourage  
 13 the child to play away from the table or from the kitchenette until all food has been taken away.  
 14 It is important to keep food out of sight and reach of children, keeping it under lock and key  
 15 if necessary (figure 8).

AQ2



16  
 17 **Figure 8.** Girl with Bardet-Biedl syndrome. You can see the amelioration of the BMI after the interdisciplinary ap-  
 18 proach to hyperphagia.

19 **11. Conclusions**

20 This chapter may bring a significant contribution to the updating of knowledge of the genetic  
 21 susceptibility and provide a better clarification of which variants are truly associated with the

1 predisposition to develop an obese phenotype. This chapter may also help to understand better  
 2 the genetic diversity that could be associated in subjects with genetic forms of obesity.  
 3 However, this chapter may help to understand this complex problem and the different  
 4 approaches to treatment. In these forms of genetic obesity, the team approach to therapy (nurse  
 5 educators, nutritionists, exercise physiologists, and counsellors) is the basis for treatment.  
 6 Dramatic reductions in BMI are difficult to achieve and sustain, so counselling and therapy  
 7 should start with realistic goals that emphasize gradual reductions of body fat and BMI and  
 8 maintenance of weight loss. Finally, this chapter may provide news on the need for new  
 9 therapeutic approaches in the field of childhood obesity as the basis of the hyperphagia  
 10 treatment, a typical feature of these syndromes.



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AQ3

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## 15 Author details

16 Stefano Stagi<sup>1\*</sup>, Martina Bianconi<sup>1</sup>, Maria Amina Sammarco<sup>1</sup>, Rosangela Artuso<sup>2</sup>,  
 17 Sabrina Giglio<sup>2</sup> and Maurizio de Martino<sup>1</sup>

18 \*Address all correspondence to: stefano.stagi@yahoo.it

19 <sup>1</sup> Health Sciences Department, University of Florence, Anna Meyer Children's University  
 20 Hospital, Florence, Italy

21 <sup>2</sup> Genetics and Molecular Medicine Unit, Anna Meyer Children's University Hospital, Flor-  
 22 ence, Italy

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