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RESEARCH ARTICLE

The Impact of Following Solid Food Feeding Guides on BMI Among Infants: A Simulation Study

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Introduction: There are several recommendations advising caregivers when and how to introduce solid food to infants. These complementary feeding guides vary in terms of the recommendations for timing and portions. The objective of this study is to determine the impact of following different guidelines on weight trajectories of infants.

Methods: In 2018, the study team developed a computational simulation model to capture feeding behaviors, activity levels, metabolism, and body size of infants from 6 months to 1 year. Daily food intake of virtual infants based on feeding recommendations translated to changes in body weight. Next, simulations tested the impact of the following complementary feeding recommendations that provided amount, type, and timing of foods: Children's Hospital of Philadelphia, Johns Hopkins Medicine, Enfamil, and Similac.

Results: When virtual caregivers fed infants according to the four different guides, none of the simulated situations resulted in normal weight at 12 months when infants were also being breastfed along average observed patterns. Reducing breast milk portions in half while caregivers fed infants according to complementary feeding guidelines resulted in overweight BMIs between 9 and 11 months for Children's Hospital of Philadelphia, Johns Hopkins Medicine, and Enfamil guidelines. Cutting breast milk portions in half also led to infants reaching unhealthy underweight BMI percentiles between 7 and 11 months for female and male infants when caregivers followed Children's Hospital of Philadelphia, Johns Hopkins Medicine, and Similac guidelines.

Conclusions: This study identified situations in which infants could reach unhealthy weights, even while following complementary feeding guidelines, suggesting that current recommended portion sizes should be tightened.
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INTRODUCTION

One key decision caregivers of infants must make is how and when to introduce solid food to an infant's diet, which in turn can drive various health and developmental outcomes. A wealth of guidelines from authorities—including the Centers for Disease Control and Prevention (CDC),[1] American Academy of Pediatrics (AAP),[2] and the U.S. Department of Agriculture's Special Supplemental Nutrition Program for Women, Infants, and Children[3]—exist to assist in decisions related to timing the introduction of solids, otherwise known as complementary foods, and what to avoid in the first year; however, guidelines vary appreciably in how much and what types of foods to provide. Bright Futures guidelines for pediatricians from the AAP emphasize the need for responsive feeding.[4] By

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recognizing hunger cues and feeding on demand, caregivers prioritize infants' metabolic regulatory mechanisms, rather than overriding them, to feed appropriately.[5]

Other nonprofit health organizations, experts, and infant feeding industry specialists, such as the Children's Hospital of Philadelphia (CHOP),[6] Johns Hopkins Medicine,[7] Enfamil,[8] and Similac[9] offer guidelines for caregivers regarding how and when to introduce solids. The extent to which guides address type and amount of food varies significantly. Feeding guidelines can assist caregivers to promote healthy growth in early childhood, but the caregivers must be able to understand and adhere to the guidelines.

Randomly assigning caregivers to follow current infant feeding guidelines through a prospective study presents ethical challenges because if a study requires an infant to eat a certain way, they are stuck with the resulting health consequences. Furthermore, it would be challenging to retrospectively track infant consumption because previous intake studies and surveys rely on parental recall and report rather than objective measures. However, using computational simulation models, different recommendations for the introduction of solid food can be tested in a "virtual laboratory" before implementing recommendations in real life. The objective of this study was to determine the potential impact of feeding guidelines on growth using a virtual infant computational simulation model. The infant model represents daily feeding behaviors, physical activity, metabolism, and the resulting changes in body size. The hypothesis of this study is that current feeding guidelines may lead to unhealthy weights.

METHODS

Virtual Infant Model

The virtual infant agent-based model was developed in Python, which can represent an infant or a group of different infants as they proceed in 1-day time steps from birth. An agent-based model was developed because the two hallmarks of agent-based modeling—autonomous decision making and complex, adaptive behavior—were necessary to represent feeding dynamics. This model utilized the modeling software platform that the study team developed.[10−12] The model included autonomous decision making so that each infant and caregiver pair could make decisions independent of other pairs. The model also included complex adaptive behavior to represent how a caregiver may change the way they feed their infant with time, depending on earlier feeding patterns and the resulting impact on the infant. Similar to a real infant, each virtual infant had a variety of characteristics including sex, starting length, starting weight, and starting BMI. The length of the virtual infant matched a reference weight based on assigned BMI percentile. Weight matched to reference values for energy demand from organs, fat mass (FM), and fat-free mass (FFM).[13−15] For each simulation run, each agent had a starting length that was assigned from the 5th to 85th WHO reference length percentiles (normally distributed around the 50th percentile). Based on the assumption that linear growth follows expected patterns during childhood,[16−20] each agent's length grew at a rate that followed the expected curve determined by the WHO growth charts[21] as the best accepted reference for children aged <2 years.[22,23] Agents grew along the expected curve if energy intake was sufficient; if intake was not sufficient, stunting occurred. Catch-up growth could follow stunting if subsequent intake exceeded requirements.

Embedded within each infant was a metabolic model drawn from previously published models.[24,25] With each time step, the metabolic models translated caloric consumption and expenditure into weight gain or loss. At each time step, a virtual infant consumed calories according to their age and specifications of the feeding guideline being tested. After the ingestion of daily total calories, they entered the embedded metabolic model and were applied to energy needs. The consumed calories first satisfied caloric needs from the basal metabolic rate (BMR), the physical activity levels, the thermic effect of feeding (TEF), and the effect of adaptive thermogenesis—all of which contributed to the total energy expenditure equation as follows:

Total energy expenditure = BMR + TEF + adaptive thermogenesis + physical activity.

The BMR is the energy (calories) needed to maintain life-sustaining functions when resting. It was calculated by summing the energy needs for FM and FFM of the infant and the energy needed for each organ.[25] TEF refers to calories that are burned off as heat during metabolic processes (e.g., breaking down food).[25] Adaptive thermogenesis accounts for how bodies slow down metabolism when energy intake is lower than usual and speed up metabolism when intake is higher than usual.[25] Specific parameters for each component are provided in the Appendix (available online). Calories from BMR, TEF, and thermogenesis were added together and then subtracted from the total energy intake observed in Butte's seminal study[26] on infant energy expenditure to obtain daily calories burned from physical activity. As the model represented each component of daily total energy expenditure, it could determine the daily caloric intake relative to the number of calories needed to maintain weight.

If the energy intake from calories was higher than the energy needed to maintain weight, the infant would gain extra weight. If the energy intake from calories failed to meet energy needs, the virtual infant metabolized energy stores, resulting in a decrease in weight.

For each time step, the model calculated changes in FM and FFM by multiplying each energy gap (difference in energy consumed and energy expended) times the amount of energy required to maintain function in each different tissue. The sum of the new FM and FFM equaled the new weight (kg) for the agent at the start of the next day.

This analysis used the CDC cut points at the 85th BMI percentile (for overweight) and 95th BMI percentile (for obesity).[27] BMI percentiles were used as a healthy weight indicator among infants (aged 0−2 years) instead of the AAP recommendation to use the weight-for-length standard.[28] A previous study by Roy et al.,[29] which suggests that BMI is a better indicator of future obesity risk, provided the basis for this decision. The BMI percentile captures changes more accurately in FM and FFM, whereas weight-for-length assesses age-specific patterns of growth.

To represent caregivers adaptively feeding their infants, caregiver agents assessed, weekly, if and how to adjust their infant's complementary feeding portion sizes while feeding within the recommended amounts. If an infant was gaining or losing weight and had crossed a major BMI percentile line (5th, 10th, 25th, 50th, 75th, 90th, and 95th) within the last week, they adjusted the feeding profile to offer portions on the lower (if increasing BMI) or upper (if decreasing BMI) end of the range. For the upper and lower end of the range, the normal distribution was truncated at the mean or upper/lower quartile depending on the scenario. For the upper portion, either the mean or upper quartile was the new minimum; for the lower portion, the mean or lower quartile was the new maximum. If an infant was already consuming the lower end of the range, then they would continue to consume portions at the lower end. If an infant was at the upper end, then they changed to normal distribution. If an infant was changing profiles, they only made one adjustment at a time (e.g., move upper to normal; they would not move from the upper to lower). When infants had doctors' appointments during complementary feeding (at 6 and 9 months according to AAP), the doctor checked the BMI. At 9 months, doctors checked the infant's BMI and compared it with their BMI at 6 months; if it had crossed a major percentile line, the caregiver would adjust the complementary food portions as described above.

Validation of Simulation Model

To validate the model, virtual caregivers fed virtual infants (15th−85th BMI percentile) the age- and BMI percentile−specific total energy requirements from Butte[26]; the resulting weights were compared with those of the cohort studied by the National Health and Nutrition Examination Survey and WHO growth curves, and they were not statistically different.[21,30] For example, a 50th BMI percentile virtual female infant weighed 6.058 kg at age 3 months (vs 5.84 kg on the WHO growth curve), 7.376 kg at age 6 months (vs 7.297 kg on the WHO growth curve), and 8.244 kg at age 9 months (vs 8.225 kg on the WHO growth curve). The infant's weight was also validated when the fed energy requirements per Butte's observed energy needs[26], among infants in the top three BMI percentiles, compared with the WHO growth curves, and the trajectory followed the same pattern; although this extreme scenario did not as closely match the average weights compared with the 15th−85th percentile BMIs (Appendix Figure 1, available online).

Testing Different Feeding Guidelines and Profiles

The study team simulated the impact of virtual caregivers and infants adhering to the following complementary feeding guidelines: (1) CHOP,[6] (2) Johns Hopkins Medicine,[7] (3) Enfamil,[8] and (4) Similac.[9] Recommendations that fell within the CDC/WHO guidelines and provided portion size guidelines were chosen because they allowed for parameterization of the complementary food that an infant would likely consume under the guide. Others, including AAP and Bright Futures guides, did not specify portion sizes. Table 1 summarizes parameters for each feeding profile. Caregivers fed breast milk to infants according to average human milk portion sizes in developed countries from the Dewey study (Table 2).[31] The 6- to 12-month period of life was simulated to represent the extent of complementary feeding recommendations. All feeding guidelines that were tested in this study recommended introducing solid food at 6 months. For each guideline, the following situations were simulated: (1) caregivers checked infant BMI each week and adjusted to the lower/upper half of the recommended portion size range depending on infant growth; (2) caregivers checked infant BMI each week and adjusted to the lower/upper quartile of the recommended portion size range depending on infant growth; (3) caregivers did not make adjustments and decided on the amount to feed infants from normal distribution of the full range of portion sizes; and (4) caregivers did not make adjustments and decided on the amount to feed infants from the lower quartile of portion sizes. Given that most guides noted that infant hunger levels were likely to vary based on the amount of breast milk they were receiving, sensitivity analyses varied the amount of breast milk that caregivers fed infants. In one scenario, caregivers fed infants 50% of breast milk and in another scenario, caregivers did not feed virtual infants any breast milk. Each scenario consisted of simulating the virtual infant 1,000 times for 180 days. Each month was 30 simulated days.

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RESULTS

Figure 1 shows BMI percentile trajectories when caregivers fed virtual infants according to the aforementioned scenarios.

When caregivers followed CHOP recommendations, no situations resulted in maintaining normal BMI (5th−85th percentile) by the end of 12 months. Across all scenarios, male and female infants' BMI moved into the overweight category by 9 months, with both female and male infants reaching the 100th percentile by 12 months.

Across all situations, when caregivers followed Johns Hopkins Medicine recommendations, infants reached the overweight category by 9.5 months for male infants and 9 months for female infants, and all infants reached the 100th percentile by 10 months.

No scenario resulted in maintaining a healthy weight by the end of the 12 months when caregivers fed infants according to the Enfamil-recommended portions. Male and female infants of caregivers who made weekly decisions about adjusting portion sizes and chose from the lower quartile reached the overweight category at 7.5 months. Male and female infants of caregivers who did not make weekly adjustments and chose portion sizes from the normal distribution of portion sizes also reached the overweight category at 7.5 months.

No scenario led to infants maintaining normal weight at 12 months, although when caregivers adjusted and chose from lower/upper quartiles, infants did not reach overweight until age 10 months in female infants and 11 months in male infants. When caregivers fed infants from the lower quartile of portion sizes without adjusting, they reached overweight at 10.5 and 11 months for female and male infants, respectively. This was the nearest to a healthy outcome of any evaluated recommendation source.

Table 1. Guideline Parameters

Age in months	Grains, semisolid (tbsp) (kcal/g)	Grains, solid (tbsp) (kcal/g)	Juices (Fl oz) (kcal/g)	Vegetables (tbsp) (kcal/g)	Fruits (tbsp) (kcal/g)	Protein-rich foods (tbsp) (kcal/g)	Dairy products (tbsp) (kcal/g)
Children's Hospital of Philadelphia recommendations[6]							
0	—	—	—	—	—	—	—
1	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—
3	—	—	—	—	—	—	—
4	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—
6	(3–5)[a] (2.28)	—	—	(1–4) (0.47)	(1–4) (0.70)	—	—
7	(3–5) (2.05)	—	—	(1–4) (0.50)	(1–4) (0.72)	—	—
8	(5–8) (2.05)	(1–2) (2.73)	(4–6) (0.41)	(4–6) (0.50)	(4–6) (0.72)	(2–4) (1.73)	(0–6) (1.86)
9	(5–8) (2.05)	(1–2) (2.73)	(4–6) (0.41)	(4–8) (0.50)	(4–8) (0.72)	(4–6) (1.73)	(0–6) (1.86)
10	(5–8) (2.01)	(8–16) (2.75)	(4–6) (0.39)	(4–8) (0.54)	(4–8) (0.75)	(4–6) (1.74)	(0–6) (1.87)
11	(5–8) (2.01)	(8–16) (2.75)	(4–6) (0.39)	(4–8) (0.54)	(4–8) (0.75)	(4–6) (1.74)	(0–6) (1.87)
12	(5–8) (1.86)	(8–16) (2.87)	(4–6) (0.40)	(4–8) (0.60)	(4–8) (0.73)	(4–6) (1.87)	(0–6) (1.86)
Johns Hopkins Medicine recommendations[7]							
0	—	—	—	—	—	—	—
1	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—
3	—	—	—	—	—	—	—
4	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—
6	(3–5) (2.28)	—	—	(1–4) (0.47)	(1–4) (0.70)	—	—
7	(3–5) (2.05)	—	—	(1–4) (0.50)	(1–4) (0.72)	—	—
8	(5–8) (2.05)	(1–2) (2.73)	—	(4–6) (0.50)	(4–6) (0.72)	—	(0–6) (1.86)
9	(5–8) (2.05)	(1–2) (2.73)	—	(4–8) (0.50)	(4–8) (0.72)	(4–6) (1.73)	(0–6) (1.86)
10	(5–8) (2.01)	(8–16) (2.75)	—	(4–8) (0.54)	(4–8) (0.75)	(4–6) (1.74)	(0–6) (1.87)
11	(5–8) (2.01)	(8–16) (2.75)	—	(4–8) (0.54)	(4–8) (0.75)	(4–6) (1.74)	(0–6) (1.87)
12	(5–8) (1.86)	(8–16) (2.87)	—	(4–8) (0.60)	(4–8) (0.73)	(4–6) (1.87)	(0–6) (1.86)
Enfamil recommendations[8]							
0	—	—	—	—	—	—	—
1	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—
3	—	—	—	—	—	—	—
4	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—

(*continued on next page*)

Ferguson et al / Am J Prev Med 2019;57(3):355−364

Table 1. Guideline Parameters (*continued*)

Age in months	Grains, semisolid (tbsp) (kcal/g)	Grains, solid (tbsp) (kcal/g)	Juices (Fl oz) (kcal/g)	Vegetables (tbsp) (kcal/g)	Fruits (tbsp) (kcal/g)	Protein-rich foods (tbsp) (kcal/g)	Dairy products (tbsp) (kcal/g)
6	(4–8) (2.28)	—	—	(0.067–1.3) (0.47)	(0.067–1.3) (0.70)	(0.067–1.3) (1.57)	—
7	(4–12) (2.05)	(2–6) (2.73)	—	(4–8) (0.50)	(6–10) (0.72)	(2–8) (1.73)	—
8	(4–12) (2.05)	(2–6) (2.73)	—	(4–8) (0.50)	(6–10) (0.72)	(2–8) (1.73)	—
9	(4–6) (2.05)	(8–10) (2.73)	—	(4–8) (0.50)	(4–12) (0.72)	(4–8) (1.73)	(2–8) (1.86)
10	(4–6) (2.01)	(8–10) (2.75)	—	(4–8) (0.54)	(4–12) (0.75)	(4–8) (1.74)	(2–8) (1.87)
11	(4–6) (2.01)	(8–10) (2.75)	—	(4–8) (0.54)	(4–12) (0.75)	(4–8) (1.74)	(2–8) (1.87)
12	(4–6) (1.86)	(8–10) (2.87)	—	(4–8) (0.60)	(4–12) (0.73)	(4–8) (1.87)	(2–8) (1.86)
Similac recommendations[9]							
0	—	—	—	—	—	—	—
1	—	—	—	—	—	—	—
2	—	—	—	—	—	—	—
3	—	—	—	—	—	—	—
4	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—
6	(3–4) (2.28)	—	—	—	—	—	—
7	(3–4) (2.05)	—	—	(3–5) (0.50)	(3–5) (0.72)	—	—
8	(2–4) (2.05)	(2–4) (2.73)	—	(4–5) (0.50)	(4–8) (0.72)	(1) (1.73)	—
9	(2–4) (2.05)	(2–4) (2.73)	—	(4–8) (0.50)	(4–8) (0.72)	(1) (1.73)	—
10	(2–4) (2.01)	(2–4) (2.75)	—	(4–8) (0.54)	(8–12) (0.75)	(1–4) (1.74)	(8) (1.87)
11	(2–4) (2.01)	(2–4) (2.75)	—	(4–8) (0.54)	(8–12) (0.75)	(2–4) (1.74)	(8) (1.87)
12	(2–4) (1.86)	(2–4) (2.87)	—	(4–8) (0.60)	(8–12) (0.73)	(2–4) (1.87)	(8) (1.86)

[a]For example, an infant of 6 months would consume 3–5 tablespoons of semisolid grains each day.
kcal, kilocalorie; tbsp, tablespoon.

Table 2. Calories From Breast Milk[31]

Months	Calories
6–8	486
9–11	375
12	313

Reducing breast milk portions in half while following solid feeding guides resulted in overweight BMIs between 9 and 11 months for CHOP, Johns Hopkins Medicine, and Enfamil (Figure 2). All Similac scenarios resulted in normal BMI percentiles at 12 months, except when caregivers did not adjust and fed male infants from the lower quartile. However, they all reached unhealthy underweight BMI percentiles at some point between 7 and 11 months for female and male infants.

When caregivers completely eliminated breastfeeding while following solid feeding guidelines, infants moved into unhealthy weight categories at some point during the 6- to 12-month period for all guidelines and all simulated scenarios of caregivers feeding infants; however, some situations did result in healthy weights at the end of 12 months, such as when caregivers adjusted to lower/upper quartiles of recommended portion size ranges for CHOP, Johns Hopkins Medicine, and Enfamil. Appendix Figure 2 (available online) shows that in later months (9−12) when recommendations expand what is allowable, there was a sudden increase in BMI percentiles.

DISCUSSION

This study shows how following existing complementary feeding guidelines can result in overfeeding infants, which subsequently could lead to infants becoming overweight or obese. Infancy can be a critical time for weight control as an infant's weight may ultimately affect their weight in childhood and adulthood.[32−34] Therefore, it is important to ensure that any infant feeding recommendations do not inadvertently lead to unhealthy weight gain.

There are concerns that caregivers may be overfeeding infants and thus overlooking natural feeding cues. Such overfeeding and larger portion sizes may be a key driver of weight gain among infants.[27] As the nature of food changes, with more calorie-dense food items available, and with the increase of distractions, caregivers may need more guidance on how much to feed their infants. Therefore, type and quantity of recommended portions listed in CHOP, Johns Hopkins Medicine, Enfamil, Similac, and other guidelines may have increasing importance.

Evidence suggests that caregivers are not necessarily following available recommendations, which may be due, at least in part, to the lack of information on the impact of adhering versus not adhering to recommendations. Each guideline examined in this study recommended introducing solid foods at 6 months; however, Feeding Infants and Toddlers 2016[35] found that caregivers often introduce solid foods earlier than 6 months —17% of infants aged 0−3.9 months and 73% of infants aged 4−5.9 months consumed complementary food on the day of the survey. Each of the four guidelines also recommended introducing fruits and vegetables after `6 months, and according to Feeding Infants and Toddlers, only 74% of infants aged 6−12 months consumed fruits and 72% consumed vegetables. With the plethora of recommendations for feeding infants now available through social media groups, websites, blogs, food manufacturer advertising, and books, it may be particularly important for feeding recommendations to be specific and demonstrate potential effects of following versus not following them.

An important component of recommendations is the portion size guideline. Recommendations for healthy portion sizes are a crucial resource to promote healthy weight gain, yet entities such as CDC and WHO do not provide portion sizes as part of their feeding guides. It is not clear how entities that do provide recommended amounts derived portion size recommendations. In the past, developing guidelines for healthy portion sizes presented challenges in both the complexity of the task and ethical considerations associated with clinical trials in infant feeding. Now, advanced computational modeling can simulate this complexity and circumvent limitations presented by the need to observe effects in actual infants. This model can serve as a "virtual laboratory" to iteratively test the impact of different complementary feeding recommendations in an effort to further refine and shape recommendations. By demonstrating the impact of guidelines, this model helps bridge the gaps between research, policy, and practice.

Limitations

Computational models are simplifications of reality and cannot include all factors that affect feeding in infants. Simulations did not account for potential reductions or increases in feeding during illnesses and sleep disturbances. Some studies indicate that macronutrients can affect linear growth and weight gain in infants, but the model does not treat a protein calorie different from a fat or carbohydrate calorie.[36] To capture infants growing at a healthy rate, the model simulated infants maintaining the percentile curve of their birth length over the first year of life. This study, similar to existing recommendations, assumes healthy infants over the first year of life. Similarly, this study assumes that feeding recommendations

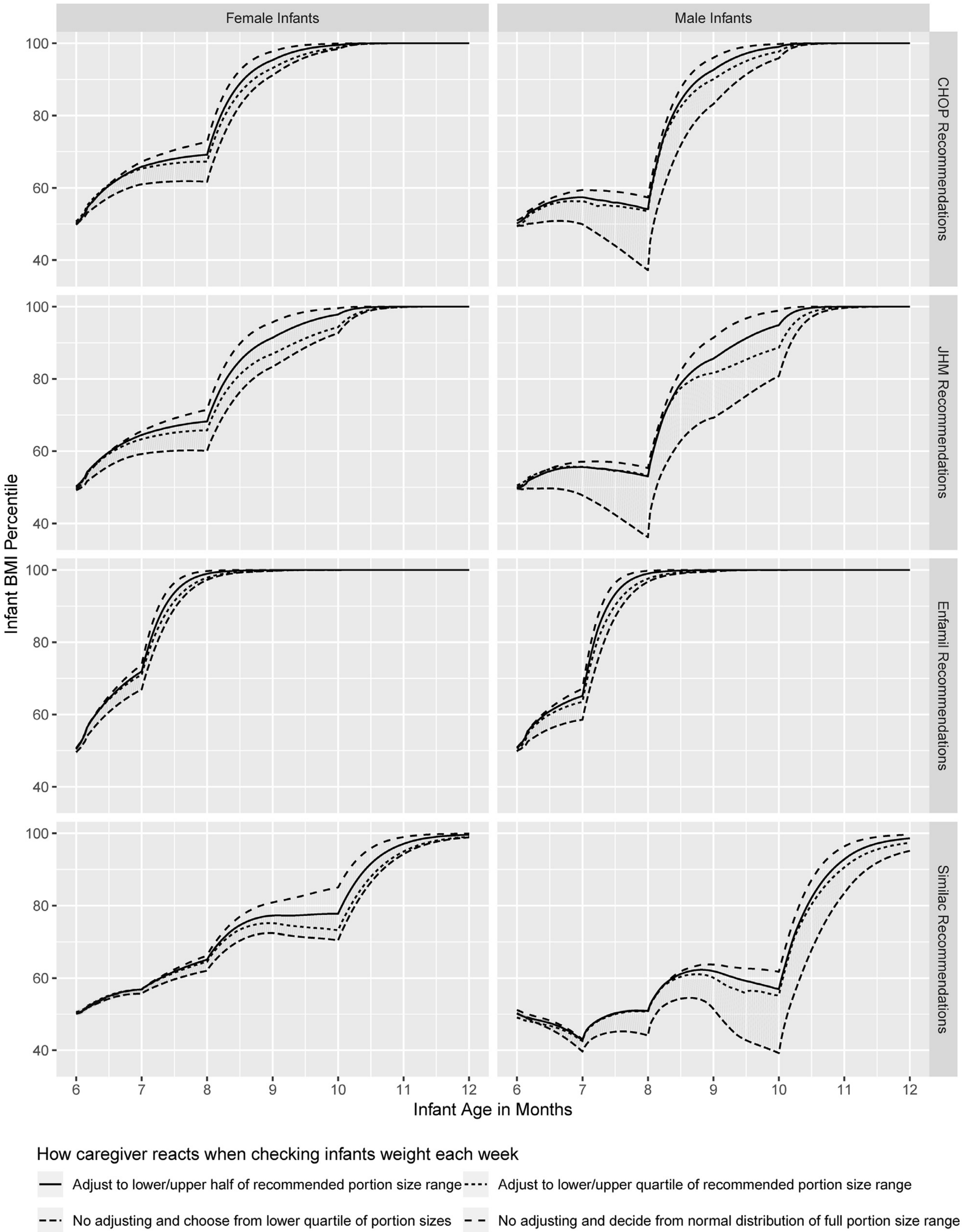

Figure 1. Impact of guideline portions on BMI percentile in the first year of life.
CHOP, Children's Hospital of Philadelphia; JHM, Johns Hopkins Medicine.

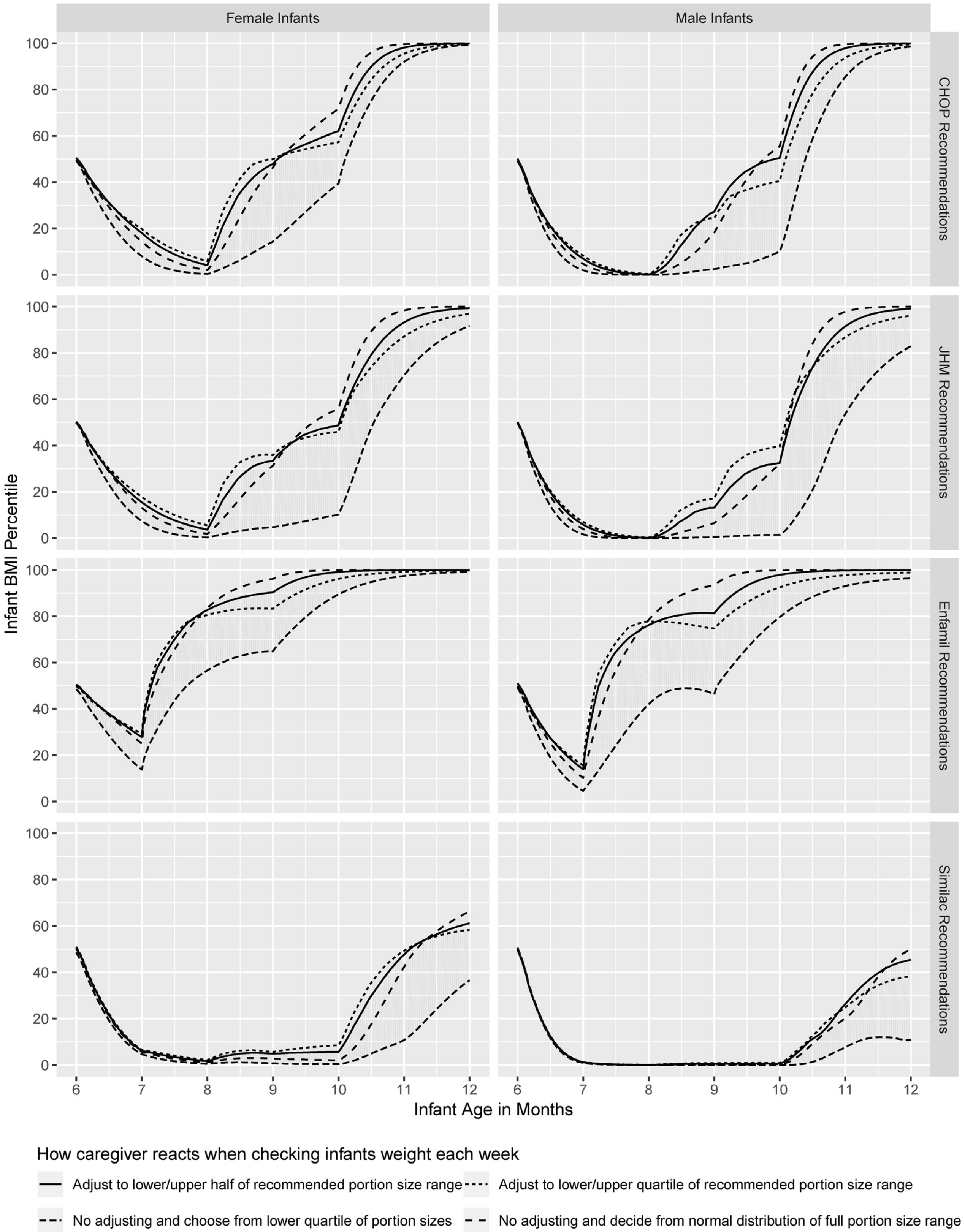

Figure 2. Impact of guideline portions on BMI percentile when breast milk portions are reduced by 50%.
CHOP, Children's Hospital of Philadelphia; JHM, Johns Hopkins Medicine.

would have the same efficacy regardless of caregiver health status, number of siblings, and economic status. This study focuses on what might happen if caregivers consistently fed infants portions within the guidelines to represent a precise interpretation of guidelines, despite any feedback regulation of appetite or feeding cues.

CONCLUSIONS

This study shows that existing complementary feeding guidelines have a high likelihood of resulting in overfeeding within the first year of life. Feeding experts and pediatricians should focus on providing tighter complementary feeding guidelines to caregivers, particularly in the later months of the first year of life. In addition, expert organizations and governing bodies could develop guidelines on how to adjust complementary feeding portion sizes and food types when the primary feeding method (i.e., breast milk or formula) diverges from recommendations around duration, intensity, or form.

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Author contributions were as follows: MCF, KJO, DLH, NJS, and LEW contributed to model development; MCF and BYL guided model development; MCF, KJO, LDH, SSS, and BYL contributed to results' analysis; MCF, KJO, LDH, SSS, and BYL contributed to manuscript writing; MCF, KJO, and BYL guided simulation experiments; MCF and KJO parameterized model; DLH, NJS, and LEW contributed to model programming; and DLH, NJS, and LEW ran model simulations. All authors approved the final manuscript and agreed to be accountable for all aspects of the work.

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SUPPLEMENTAL MATERIAL

Supplemental materials associated with this article can be found in the online version at https://doi.org/10.1016/j.amepre.2019.04.011.

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