Analysis of the Nonlinear Dynamics of Daily Broiler Growth and Feed Intake

K. J. Vandegrift, T. L. Cravener, R. M. Hulet, and W. B. Roush[1]

Department of Poultry Science, Pennsylvania State University, University Park, Pennsylvania 16802-3501

ABSTRACT Daily BW velocity (BWV) and acceleration (BWA) of individual birds have been demonstrated to be oscillatory. Daily feed intake velocity (FIV) and acceleration (FIA) were hypothesized to be oscillatory and to have a positive relationship with BWV and BWA, respectively. Forty-eight male broiler chicks were individually caged and provided a commercial starter feed ad libitum for 49 d. BW and feed intake (FI) were measured daily. Experiment 1 confirmed that, on a daily basis, BWV, BWA, FIV, and FIA were oscillatory. There was a positive correlation between BW and FI, BWV and FIV, and BWA and FIA. A Kohonen neural network (KNN) clustered BWV and FIV into two and three sequential phases. BWA and FIA analysis did not make definitive clusters. In experiment 2, it was hypothesized that correlation between BWV and FIV would increase with feeding of grower and finisher rations. It was hypothesized that KNN three phase clusters may provide more biologically ideal times of ration change (TORC) for starter, grower, and finisher rations. For 49 d, five treatments, nine birds per treatment, were fed starter, grower, and finisher rations singly or together with dietary changes according to an industry or KNN-determined TORC. Evaluation was made of BW, FI, and carcass characteristics. No significant mean differences were found. Compared to the industry group, the KNN group demonstrated significantly improved uniformity (i.e., smaller SD) of BW (bled out), FI, dressing percentage, and some of the carcass characteristics. Differences between KNN and industry TORC results might have been related to the length of time the birds were fed the starter, grower, and finisher diets.

(*Key words*: growth, artificial neural network, Kohonen clustering, phase feeding, uniformity)

2003 Poultry Science 82:1091–1099

INTRODUCTION

The National Research Council (NRC, 1994) lists three growth phases for nutrient requirements during a 7-wk broiler growout period. To date, there are only a few studies to determine the time of ration change (TORC) for three types of feed (Guirguis, 1978; Proudfoot and Hulan, 1980; Roush, 1983; Saleh et al., 1996, 1997a,b). The TORC is an economically important decision, not only because of the differing price of the feeds but also because of ramifications that ration changes can have on performance. The provision of nutrients at the proper time implies improved flock and product uniformity.

Meat product uniformity is an important goal in the processing industry because it allows for a more accurate food supply and cost prediction. Highly uniform flocks are managed more efficiently due to a reduced range of nutrient requirements. In addition, the processing of uniform flocks is more easily accommodated by automated processing equipment. Today, some processors sort meat products by size and color for packaging. Variation in one piece of meat product can lead to consumer rejection of the entire package (Sams, 2001). High flock variability can lead not only to increased production costs but also to decreased market value.

Roush and Wideman (2000) have described broiler growth as volumetric motion in time, which, in turn, can be described in the terminology of physics as velocity and acceleration. Examination of the rate of growth in the context of velocity and acceleration has proven useful. Several papers (Roush et al., 1996, 1997; Roush and Wideman, 2000; Roush et al., 2001) have shown that the dynamics of the rate of day-to-day growth (velocity) and the rate of the rate of day-to-day growth (acceleration) can be used in conjunction with an artificial neural network for the diagnosis of pulmonary hypertension syndrome, an economically important disease in fast-growing broilers. Previous work by Titus et al. (1934) has shown that feed intake responses are also dynamic in nature. A question arises in how the dynamics of daily growth rate (velocity) and the daily feed intake rate (velocity) might be related and how they might be used to improve the management of the birds.

Received for publication October 29, 2002.
Accepted for publication February 26, 2003.
[1]To whom correspondence should be addressed: broush@msa-sstate.ars.usda.gov.

Abbreviation Key: BWA = body weight acceleration; BWV = body weight velocity; FI = feed intake; FIA = feed intake acceleration; FIV = feed intake velocity; KNN = Kohonen neural network; TORC = time of ration change.

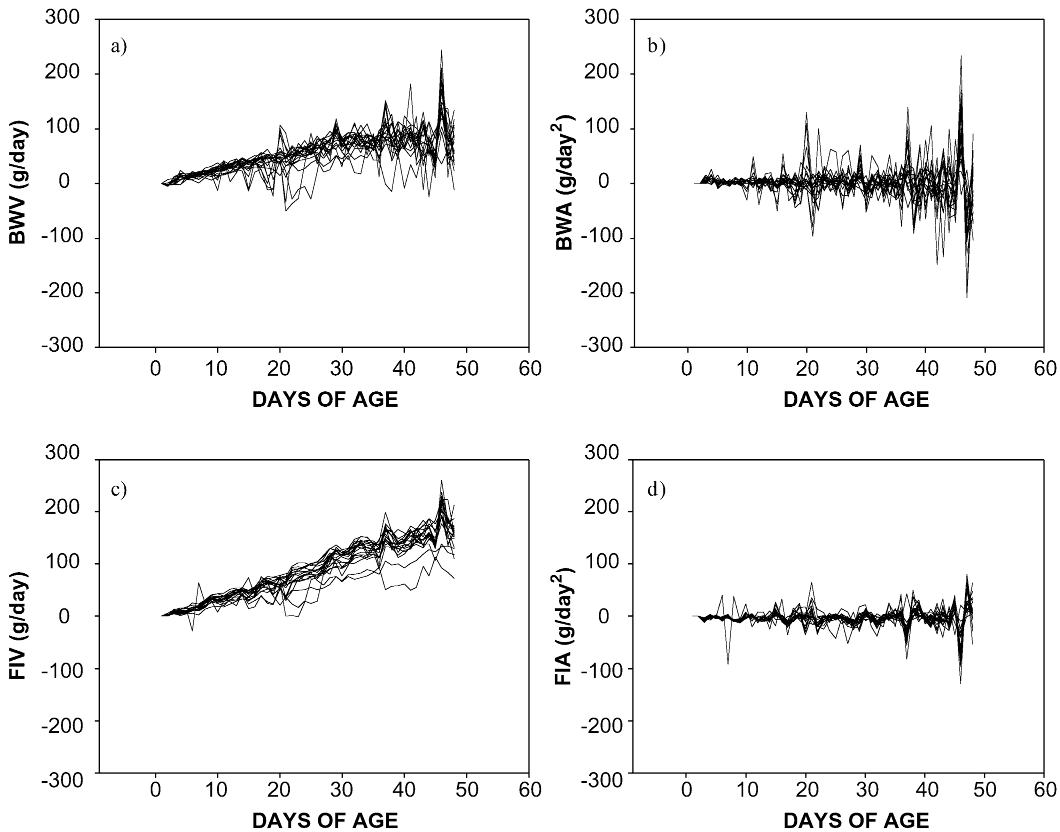

FIGURE 1. a) Body weight velocity (BWV), b) BW acceleration (BWA), c) feed intake velocity (FIV), and d) feed intake acceleration (FIA) of all birds (experiment 1).

In this study, two experiments were conducted to evaluate the dynamics of the day-to-day growth and feed intake (FI) rates of individual commercial broilers. Please note that all of the references to velocity and acceleration in these experiments were determined on a daily basis. The second study also addressed the effect of the time of ration change on broiler performance.

The first objective of experiment 1 was to evaluate the hypothesis that the daily BWV and FIV are oscillatory. The second objective was to investigate whether there is a positive relationship between BW velocity (BWV) and FI velocity (FIV), as well as between BW acceleration (BWA) and FI acceleration (FIA). Previous growth velocity and acceleration observations (Roush et al., 1994) have suggested there are temporal differences in the magnitude of growth responses, which may be characterized into three phases of growth. A third objective was to examine if a Kohonen neural network could cluster and define these growth phases.

Experiment 2 was conducted to evaluate the effects on BWV and FIV when feeding broilers starter, grower, and finisher rations singly or in combination. The ration combinations were based on the successful Kohonen clustering of responses in experiment 1 or on industry suggested times of ration change.

MATERIALS AND METHODS

Forty-eight Ross × Arbor Acre broiler chicks were caged individually in Petersime[2] brooder batteries at 1 d of age. The birds were housed with 24 h lighting in a temperature-controlled environment (95% confidence interval 26.8 to 27.7°C). At 20 d the broilers were moved to individual grower cages. In experiment 1, all of the birds were fed a crumbled commercial starter (23% CP and 3,100 ME/kg) for 49 d. In experiment 2, the birds were fed according to five dietary treatment groups with nine birds per treatment. The first three treatments consisted of crumbled commercial starter (23% CP and 3,100 ME/kg), grower (21% CP and 3,200 ME/kg), and finisher (19% CP and 3,260 ME/kg), respectively. The starter, grower, and finisher rations were each fed singly for 49 d. For the other two feeding programs, starter, grower, and finisher rations were fed in combination with diet changes based on the Kohonen neural network (KNN) clusters of experiment 1 and an industry-recommended TORC. The Kohonen group of birds received starter from 1 to 20 d, grower 21 to 30 d, and finisher 31 to 49 d. The industry group of birds received starter

[2]Petersime Centrumstraat 125—B-9870 Zulte, Belgium.

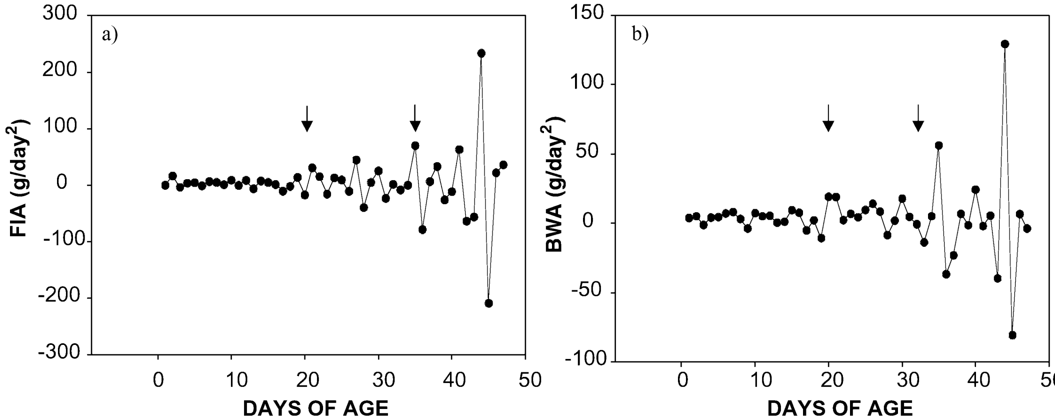

FIGURE 2. The variation of an individual bird for a) BW velocity (BWV) and b) feed intake velocity (FIV) suggests three potential phases (experiment 1).

1 to 19 d, grower 20 to 36 d, and finisher 37 to 49 d. These commercial rations met or exceeded the National Research Council (1994) nutrient requirements. All treatment groups were provided feed and water ad libitum. Light was provided on a 24-h basis. Individual BW and FI were measured at the same time each day (1100 h) for each of 49 d. BW and FI were measured with a Sartorius[3] Basic Plus analytical scale using the animal weighing function. A KNN, part of the Neuroshell 2[4] software package, was used to cluster the velocity and acceleration data.

In experiment 2, all surviving birds were killed via exsanguination and processed for carcass parts. The following carcass characteristics were measured: live weight, BW (bled out), and parts weight including breast, breast skin, breast shell, fat pad, wings, thigh, drum, neck, and back.

These experiments were conducted with the approval of the Pennsylvania State Animal Care Committee (IACUC # 00R139-00, Modeling the Biocomplexity of Animal Nutrition).

Statistical Evaluation

In both experiments, difference equations were used to calculate daily BW and FI velocity and acceleration (Roush, et al., 1994). Velocity was calculated by taking the difference between the performance values for two successive days (e.g., BWV = BW (d_{n+1}) – BW (d_n)). The acceleration was calculated by taking the difference between the velocity values of 2 successive d (BWA = BWV (d_{n+1}) – BWV (d_n)). In experiment 2, Minitab,[5] Microsoft Excel,[6] and SAS software[7] were used for regression and data analysis. To examine differences in the variability of the treatments, three independent samples were made for each production and carcass SD values of each treatment. These sample replicates for BW, FI, and carcass characteristics were evaluated for significant differences by the SAS generalized linear model[7] (GLM) at $P = 0.05$. The Duncan's multiple comparison procedure (Duncan, 1955) was used to determine significant differences among the treatment groups. Microsoft Excel was used for calculation of the percentage growth and FI. Figures were plotted using Sigma Plot.[8]

Neural Network Analysis

A Ward Systems KNN, a component of the NeuroShell2 software package, was employed to cluster the velocity and acceleration data. The Kohonen network is an unsupervised network with the ability to learn without being shown correct outputs in sample patterns. These networks are able to separate data into a specified number of clusters.

Kohonen networks have two layers. The first layer has the number of inputs, and the second layer contains the maximum number of groups in which the inputs should be clustered. Based on the observations of Roush et al. (1994), FIV, BWV, FIA, and BWA were evaluated to determine if they could be classified into two, three, four, and five clusters.

The KNN pattern selection was in rotation, in which, the training data were selected in the order of occurrence

TABLE 1. Coefficient of determination values for the relationships of BW and feed intake (FI), BW velocity (BWV) and FI velocity (FIV), and BW acceleration (BWA) and feed intake acceleration (FIA) (experiment 1)

X vs. Y	r^2	Probability
BW vs. FI	0.902	0.0001
BWV vs. FIV	0.601	0.0001
BWA vs. FIA	0.406	0.0001

[3]Weender Landstrasse, Goettingen, Germany.
[4]Ward Systems Group, Inc., Frederick, MD.
[5]Minitab Inc., State College, PA.
[6]Microsoft, Inc., Redmond, WA.
[7]SAS Institute, Inc., Cary, NC.
[8]SPSS Science, Chicago, IL.

TABLE 2. Kohonen neural network clusters for three time phases of BW velocity responses over 48 d for all birds (experiment 1)

BW velocity				FI velocity			
Day	Phase 1	Phase 2	Phase 3	Day	Phase 1	Phase 2	Phase 3
1	1	0	0	1	1	0	0
2	1	0	0	2	1	0	0
3	1	0	0	3	1	0	0
4	1	0	0	4	1	0	0
5	1	0	0	5	1	0	0
6	1	0	0	6	1	0	0
7	1	0	0	7	1	0	0
8	1	0	0	8	1	0	0
9	1	0	0	9	1	0	0
10	1	0	0	10	1	0	0
11	1	0	0	11	1	0	0
12	1	0	0	12	1	0	0
13	1	0	0	13	1	0	0
14	1	0	0	14	1	0	0
15	1	0	0	15	1	0	0
16	1	0	0	16	1	0	0
17	1	0	0	17	1	0	0
18	1	0	0	18	1	0	0
19	0	1	0	19	1	0	0
20	1	0	0	20	1	0	0
21	0	1	0	21	0	1	0
22	0	1	0	22	0	1	0
23	0	1	0	23	0	1	0
24	0	1	0	24	0	1	0
25	0	1	0	25	0	1	0
26	0	1	0	26	0	1	0
27	0	1	0	27	0	1	0
28	0	0	1	28	0	1	0
29	0	1	0	29	0	1	0
30	0	0	1	30	0	1	0
31	0	0	1	31	0	0	1
32	0	0	1	32	0	0	1
33	0	0	1	33	0	0	1
34	0	0	1	34	0	0	1
35	0	1	0	35	0	0	1
36	0	0	1	36	0	0	1
37	0	0	1	37	0	0	1
38	0	0	1	38	0	0	1
39	0	0	1	39	0	0	1
40	0	0	1	40	0	0	1
41	0	0	1	41	0	0	1
42	0	0	1	42	0	0	1
43	0	0	1	43	0	0	1
44	0	1	0	44	0	0	1
45	0	0	1	45	0	0	1
46	0	0	1	46	0	0	1
47	0	0	1	47	0	0	1
48	0	0	1	48	0	0	1

(Ward Systems Group, 1993). A learning rate was applied to the weight updates, but a momentum factor was not. Thus, the output of the network is the square of the distance between the pattern and the weight vector for that neuron. The learning rate and initial learning rate were set at the default of 0.5, and training continued for 50 epochs. During training, the network propagated the neurons from the input slab onto the second slab where they were evaluated, and one was determined the winner with the winning neurons having the smallest values. The weights were adjusted according to the learning rate, and the process was repeated for the set number of epochs. The learning rate was steadily lowered during training to converge on the solution.

RESULTS AND DISCUSSION

Experiment 1

The velocity and acceleration of BW and FI responses, as determined by sequential differencing, are shown in Figure 1. The BWV, BWA, FIV, FIA were confirmed to be oscillatory. Hendricks et al. (1932) were the first to demonstrate the oscillatory nature of cumulative ad libitum FI response. They also noted a relationship between the oscillations of BW and FI. In experiment 1, the relationship of BW and FI rates was tested with linear regression analysis. Table 1 shows a high positive relationship between BW and FI ($r^2 = 0.902$, $P = 0.0001$),

TABLE 3. Degree of fragmentation according to Kohonen neural network (KNN) clusters for BW velocity (BWV) and acceleration (BWA) and feed intake velocity (FIV) and acceleration (FIA)

Factor	KNN Clusters	Fragmentation[1] (%)
BWV	2	2/48 (4)
	3	8/48 (17)
	4	17/48 (35)
	5	16/48 (33)
FIV	2	0/48 (0)
	3	0/48 (0)
	4	2/48 (4)
	5	4/48 (8)
BWA	2	24/47 (51)
	3	18/47 (38)
	4	29/47 (62)
	5	37/47 (79)
FIA	2	27/47 (57)
	3	30/47 (64)
	4	30/47 (64)
	5	27/47 (57)

[1]Fragmentation was determined by the number of breaks between successive cluster values divided by the number of observations.

a moderate positive relationship between BWV and FIV ($r^2 = 0.601$, $P = 0.0001$), and a small, but positive, correlation between BWA and FIA ($r^2 = 0.406$, $P = 0.0001$).

In previous research, Roush, et al. (1994) suggested that the growth acceleration of a broiler followed a triphasic pattern. Figure 2 (a and b) shows an example of how the dynamics of BW and FI acceleration responses for a single bird suggest clustering growth and feed intake responses into three oscillatory phases.

To examine the hypothesis that the biological growth velocity and acceleration data would cluster into three phases, data were subjected to a KNN. BWV was clustered with some fragmentation, whereas three sequential clusters for FIV were clearly defined (Table 2).

Although the primary interest was in the three phase clusters (related to times for feeding starter, grower, and finisher rations), the data were also examined as two, four, and five clusters (not shown). In general, the FIV sequentially clustered very well into two and three clusters. For a four-cluster examination there was some fragmentations for the third and fourth clusters. For the five-cluster examination, there was fragmentation for the third, fourth, and fifth clusters. In general, BWV did not cluster as well as FIV. A quantitative evaluation of the fragmentation for BWV, BWA, FIV, and FIA is shown in Table 3. The fragmentation was determined by the number of breaks between successive cluster values divided by the number of observations.

Although examination of acceleration responses have suggested the same type of clustering, the results for the Kohonen clusters for the acceleration responses were highly fragmented and did not result in definitive clusters of sequential responses (Vandegrift, 2002). The reason for the lack of clustering for acceleration may be related to the detrending process which occurs with the sequential differencing of the velocity responses. The detrending process may have homogenized the responses thus negating the sequential clustering phenomenon.

Experiment 2

Because the Kohonen network results clustered the BWV and FIV into three phases, it was reasoned that these biological clusters might provide a biologically ideal TORC. Therefore, the hypothesis was examined that the Kohonen neural network clusters would provide a better TORC than an industry recommended TORC as measured by production responses and carcass characteristics. Secondly, the hypothesis was tested that feeding the starter, grower, and finisher rations according to the Kohonen and industry TORC would improve the correlation between BWV and FIV. The production responses examined included BW, FI, BWV, FIV, BWA, and FIA. Carcass characteristics included carcass, breast, breast skin, breast shell, fat pad, wing, thigh, drum, neck, and back weights. Figures 3 and 4 illustrate the BWV, BWA, FIV, and FIA for the KNN and industry treatment groups. It is important to note the response oscillation occurred with all three types

TABLE 4. Evaluation of means and standard deviations for broiler performance measures fed under five treatments for 49 d (experiment 2)

Treatment	Live weight (g)	Feed intake (g)	Feed conversion	Dressing (%)
Mean value				
Starter	2,862.9[a]	5,201.4[a]	1.82[a]	76.42[a]
Grower	2,890.6[a]	5,008.0[a]	1.74[a]	77.05[a]
Finisher	2,738.6[a]	4,895.0[a]	1.79[a]	75.28[a]
Kohonen	2,877.6[a]	5,168.2[a]	1.80[a]	76.03[a]
Industry	2,890.6[a]	5,142.1[a]	1.78[a]	74.79[a]
Standard deviation value				
Starter	271.8[a]	451.9[b]	0.082[a]	1.22[a]
Grower	352.7[a]	565.5[a]	0.055[a]	1.12[a]
Finisher	260.1[a]	569.7[a]	0.117[b]	2.66[b]
Kohonen	191.0[a]	383.9[b]	0.064[a]	1.62[a]
Industry	364.5[a]	681.8[a]	0.116[b]	2.54[b]

[a,b]Column means with the same superscript are not significantly different ($P < 0.05$). See the text for an explanation of the treatment groups.

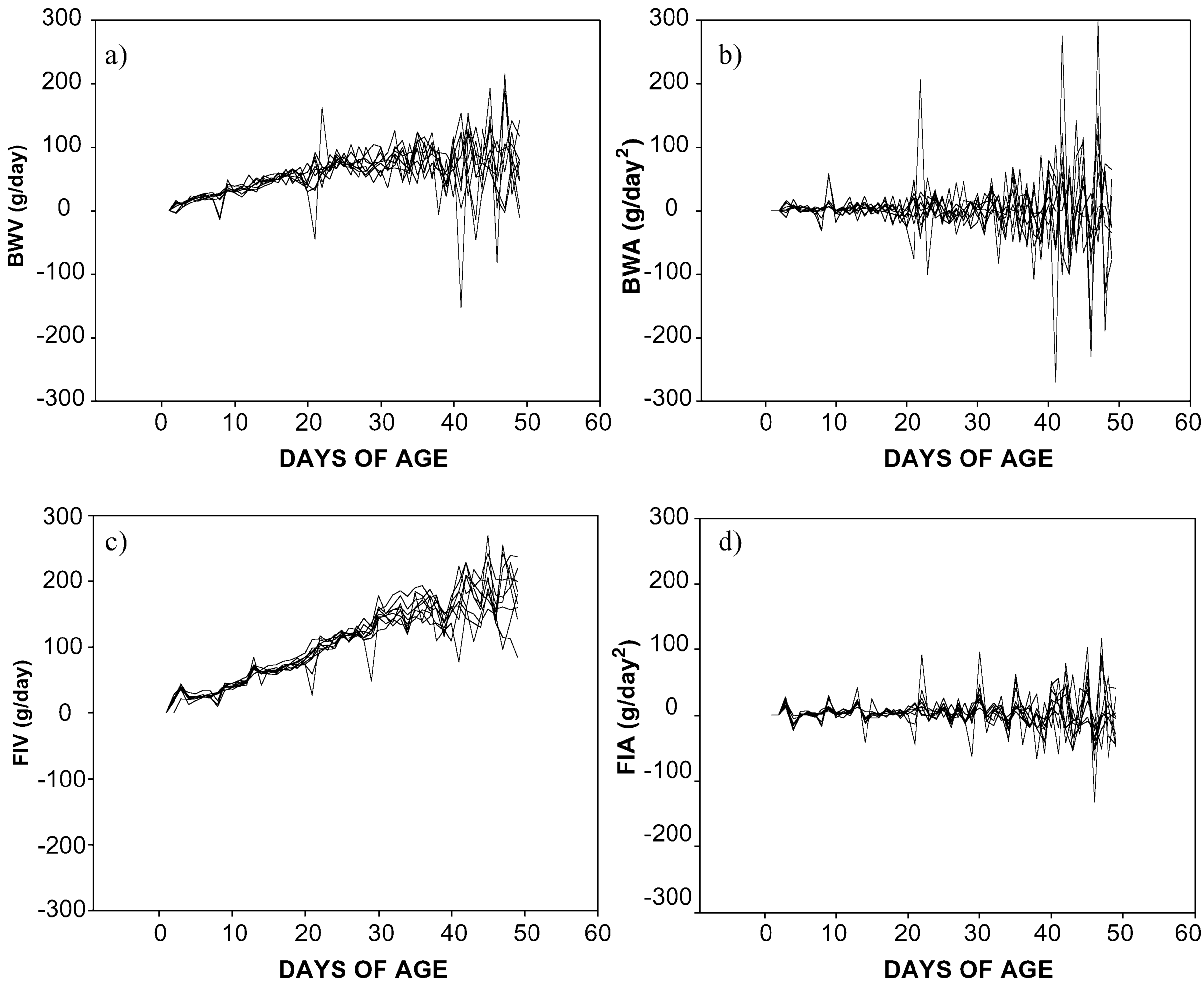

FIGURE 3. a) Body weight velocity (BWV), b) BW acceleration (BWA), c) feed intake velocity (FIV), and d) feed intake acceleration (FIA) of the Kohonen time of ration change (TORC) (experiment 2).

TABLE 5. Evaluation of means and standard deviations of carcass characteristics for broilers fed under five treatments for 49 d (experiment 2)

	BW[1] (g)	Breast (g)	Breast skin (g)	Breast shell (g)	Back (g)	Thigh (g)	Drum (g)	Wings (g)	Fat (g)	Neck (g)
Mean values										
Starter	2,640.2^{a}	564.7^{a}	100.7^{a}	283.5^{a}	199.1^{a}	348.5^{a}	282.4^{a}	223.1^{a}	16.6^{a}	71.7^{a}
Grower	2,670.9^{a}	565.6^{a}	99.2^{a}	291.9^{a}	203.5^{a}	351.2^{a}	293.4^{a}	231.3^{a}	19.5^{a}	80.0^{a}
Finisher	2,554.7^{a}	508.6^{a}	95.1^{a}	292.8^{a}	179.4^{a}	323.7^{a}	278.7^{a}	228.7^{a}	15.1^{a}	69.2^{a}
Kohonen	2,650.0^{a}	559.5^{a}	96.4^{a}	288.9^{a}	202.4^{a}	334.9^{a}	288.0^{a}	231.4^{a}	14.7^{a}	74.3^{a}
Industry	2,673.9^{a}	553.4^{a}	96.8^{a}	287.1^{a}	198.8^{a}	332.1^{a}	298.2^{a}	220.6^{a}	14.4^{a}	63.4^{a}
Standard deviation value										
Starter	273.5^{a}	50.8^{b}	15.8^{a}	42.1^{a}	34.3^{a}	51.6^{a}	29.9^{a}	27.0^{a}	6.2^{a}	8.1^{a}
Grower	305.7^{a}	69.9^{ab}	29.2^{a}	37.6^{a}	31.3^{a}	35.4^{a}	22.1^{a}	19.9^{a}	9.3^{a}	12.6^{a}
Finisher	260.8^{ab}	85.0^{ab}	19.0^{a}	36.3^{a}	22.1^{a}	72.9^{a}	22.6^{a}	14.2^{a}	10.1^{a}	5.6^{a}
Kohonen	214.8^{b}	70.9^{b}	21.0^{a}	33.7^{a}	30.9^{a}	59.5^{a}	21.5^{a}	16.7^{a}	6.1^{a}	7.0^{a}
Industry	397.9^{a}	85.4^{a}	17.5^{a}	63.2^{a}	32.0^{a}	62.1^{a}	38.5^{a}	40.1^{b}	10.1^{a}	10.5^{a}

[a,b]Column means with the same superscript are not significantly different ($P < 0.05$). See text for an explanation of the treatment groups.

[1]Carcass was bled out but not eviscerated.

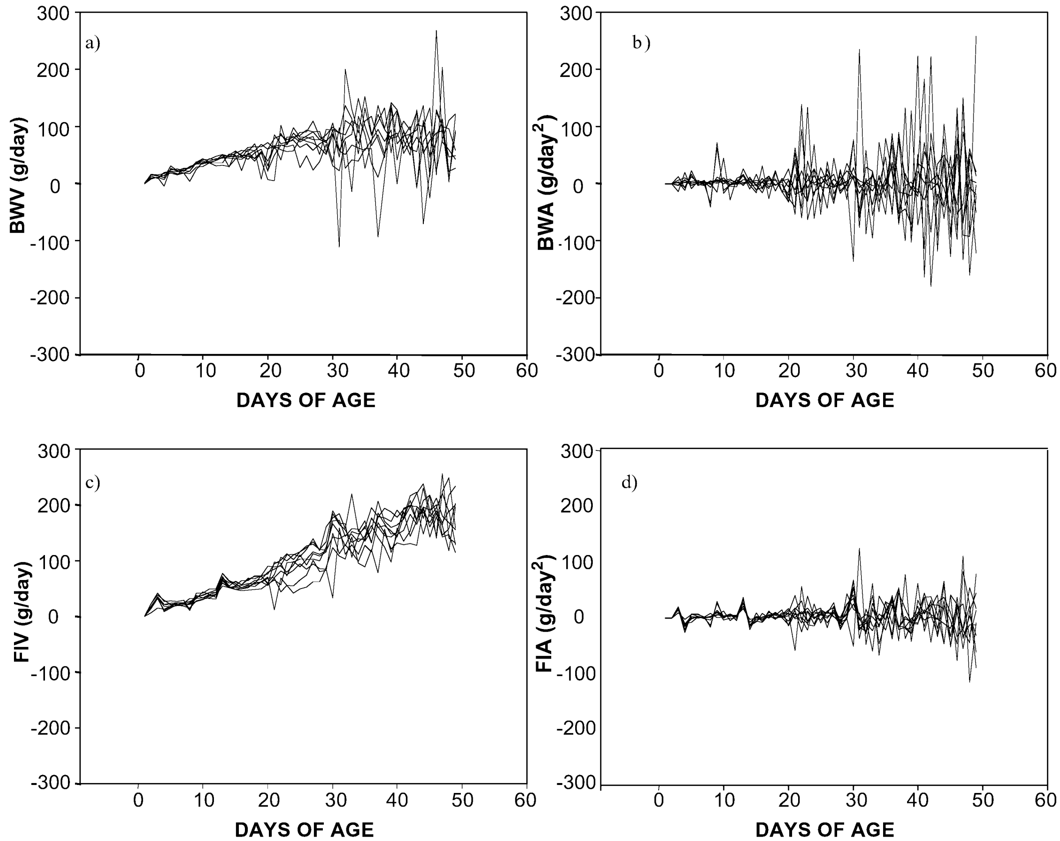

FIGURE 4. a) Body weight velocity (BWV), b) BW acceleration (BWA), c) feed intake velocity (FIV), d) feed intake acceleration (FIA) of the industry time of ration change (TORC) (experiment 2).

of feed fed singly or in combination according to the specified times of ration change. This reaffirmed the experiment 1 conclusion regarding the oscillatory nature of these responses. The ANOVA analyses revealed no significant differences between treatment groups for the means of any of the production responses (Table 4) or mean carcass characteristics (Table 5).

The hypothesis that feeding the starter, grower, and finisher rations according to the Kohonen and industry TORC would improve the correlation between BWV and FIV is not accepted. There was no improvement in coefficients of determination for the relationship between BWV and FIV for any of the treatments as compared to results in experiment 1 (Table 6).

The dispersions of the responses were examined by considering the standard deviation values as response variables (variance analysis as contrasted with analysis of variance). There were significant differences in the standard deviation values for some of the performance and carcass characteristics. These significant differences in standard deviation indicated divergence in the uniformity of the performance values and carcass characteristics. In Table 4, the Kohonen treatment group had a smaller standard deviation as compared to the Industry treatment for feed intake, feed conversion and dressing percent ($P < 0.05$). Feeding the birds a starter or grower ration alone for the 49 d period produced low standard deviations for feed conversion and yield which were comparable ($P > 0.05$) to the Kohonen treatment group.

For carcass characteristics (Table 5), there were no treatment differences ($P > 0.05$) in mean values for any of the variables. There were significant differences ($P < 0.05$) in SD in favor of the Kohonen TORC for body weight (bled out), and breast meat. The birds fed the starter ration had the smallest standard deviation for breast meat. The KNN treatment had a significantly smaller standard deviation for breast meat as compared to the industry treatment. The industry group had a significantly larger standard deviation for wings when compared to the other treatment.

A visual examination of the BWV and BWA responses for the Kohonen (Figure 3a and 3b) and industry (Figure 4a and 4b) TORC groups indicated that the degree of oscillation was smaller for the Kohonen group. This comparison also shows a greater oscillation for the in-

TABLE 6. Coefficient of determination values for the relationship of BW velocity versus feed intake velocity of birds feed different time of ration change regimens (experiment 2)

Treatment	r^2	Probability
Starter	0.533	0.0001
Grower	0.506	0.0001
Finisher	0.578	0.0001
Kohonen	0.495	0.0001
Industry	0.529	0.0001

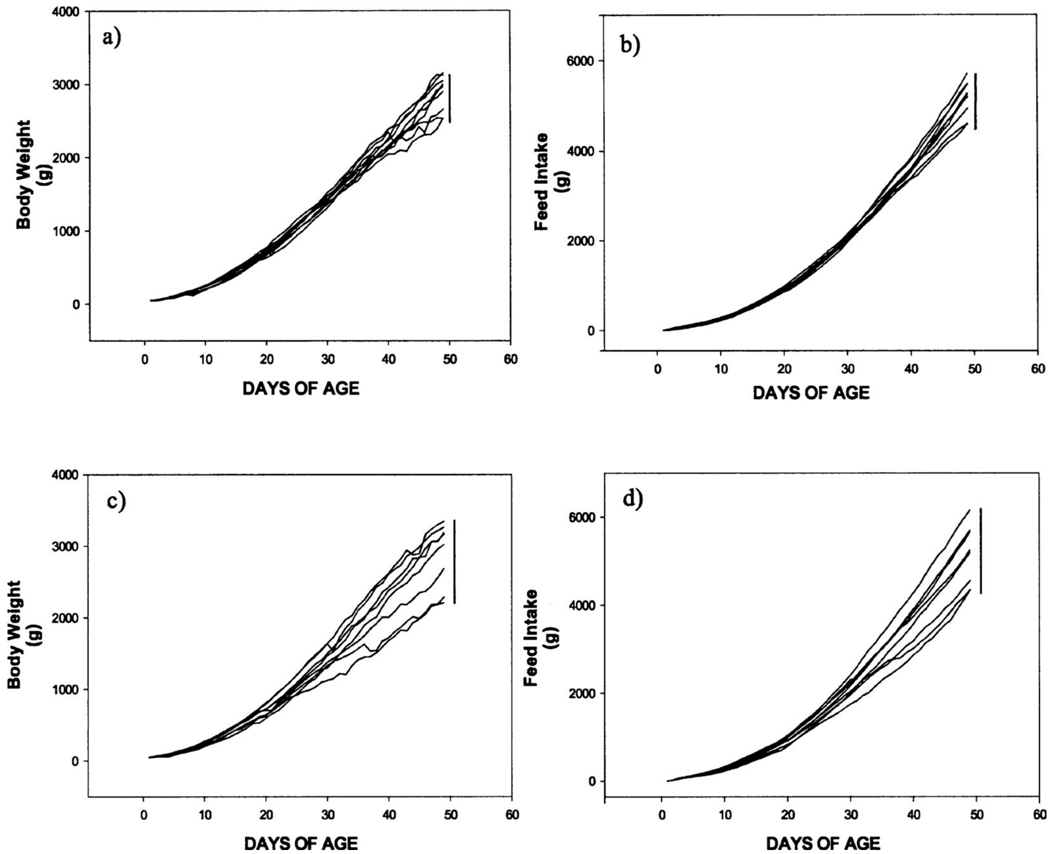

FIGURE 5. Cumulative BW and feed intake for the Kohonen and industry times of ration change (experiment 2).

dustry group especially during the 30-to-36-d period when the industry group was still receiving a grower ration. The differences in cumulative BW and FI (Figure 5) suggested the reduced variability for the Kohonen treatment. The Kohonen TORC group appears to have exhibited about half as much variation as the industry TORC group for the FI and BW responses. The differences in dispersion of responses were significant ($P < 0.05$) for the standard deviation values for FI but not BW (Table 4).

Increased product and FI uniformity is a common goal in the broiler industry to facilitate more accurate food supply and cost predictions as well as to satisfy consumer preferences. The investigation of times for feeding starter, grower, and finisher provided information that should be researched further. The timing of when rations provide nutrients affects the uniformity of the flock responses. The improved uniformity of the all-starter ration was a surprise, which warrants further investigation and cost-benefit analysis. The results of this work suggest further analysis of the time of providing ration in experiments with different genetic lines and environments may open up further opportunities to increase product and FI uniformity.

ACKNOWLEDGMENTS

This research was partially supported by agriculture research funds administered by the Pennsylvania Department of Agriculture.

REFERENCES

Duncan, D. 1955. Multiple range and F test. Biometrics 11:1–42.

Guirguis, N. 1978. Effect of dietary protein composition on the optimum time of change from starter to finisher diets for broilers. Aust. J. Exp. Agric. Anim. Husbandry 9:53–63.

Hendricks, W., M. Jull, and H. Titus. 1932. The utilization of feed by chickens. The requirements for growth. Poult. Sci. 9:74–77.

National Research Council. 1994. Nutrient Requirements of Poultry. 9th rev. ed. National Academy Press, Washington, DC.

Proudfoot, F., and H. Hulan. 1980. Performance of chicken broilers changed from starter to finisher at different ages. Can. J. Anim. Sci. 60:799–801.

Roush, W. 1983. An investigation of protein levels for broiler starter and finisher rations and the time of ration change by response surface methodology. Poult. Sci. 62:110–116.

Roush, W., G. Barbato, and T. Cravener. 1994. A nonlinear dynamical (chaos) approach to the analysis of broiler growth. Poult. Sci. 73:1183–1195.

Roush, W., Y. Kirby, T. Cravener, and R. Wideman, Jr. 1996. Artificial neural network prediction of ascites in broilers. Poult. Sci. 75:1479–1487.

Roush, W., Y. Kirby, T. Cravener, and R. Wideman, Jr. 1997. Neural network prediction of ascites in broilers based on minimally invasive physiological factors. Poult. Sci. 76:1513–1516.

Roush, W., and R. Wideman. 2000. Evaluation of broiler growth velocity and acceleration in relation to pulmonary hypertension syndrome. Poult. Sci. 79:180–191.

Roush, W., R. F. Wideman, Jr., A. Cahaner, N. Deeb, and T. L. Cravener. 2001. Minimal number of chicken daily growth velocities for artificial neural network detection of pulmonary hypertension syndrome (PHS). Poult. Sci. 80:254–259.

Saleh, E., S. Watkins, and P. Waldroup. 1996. Changing time of feeding starter, grower, and finisher diets for broilers. 1. Birds grown to 1.0 kg. J. Appl. Poult. Sci. 5:269–275.

Saleh, E., S. Watkins, and P. Waldroup. 1997a. Changing time of feeding starter, grower, and finisher diets for broilers. 1. Birds grown to 2.2 kg. J. Appl. Poult. Sci. 6:64–73.

Saleh, E., S. Watkins, and P. Waldroup. 1997b. Changing time of feeding starter, grower, and finisher diets for broilers. 1. Birds grown to 3.3 kg. J. Appl. Poult. Sci. 6:290–297.

Sams, A. 2001. Poultry Meat Processing. CRC Press, New York.

Titus, H. W., M. A. Jull, and W. A. Hendricks. 1934. Growth of chickens as a function of feed consumption. J. Agic. Res. 48:817–835.

Vandergrift, K. J. 2002. An analysis of the nonlinear dynamics of daily broiler growth and feed intake. M.S. Thesis. Pennsylvania State University, University Park, PA.

Ward Systems Group. 1993. NeuroShell 2 User's Manual. Ward Systems Group, Inc. Frederick, MD.