

SUMMARY OF RESEARCH

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**AN EVALUATION OF COLLAGEN METABOLISM IN NON
HUMAN PRIMATES ASSOCIATED WITH THE BION 11 SPACE
PROGRAM-MARKERS OF URINARY COLLAGEN TURNOVER AND
MUSCLE CONNECTIVE TISSUE.**

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BION 11 FINAL REPORT

**UNIVERSITY OF HOUSTON
CONNECTIVE TISSUE
PHYSIOLOGY LABORATORY**

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INTRODUCTION

Patients exhibiting changes in connective tissue and bone metabolism also show changes in urinary by-products of tissue metabolism. Furthermore, the changes in urinary connective tissue and bone metabolites precede alterations at the tissue macromolecular level. Astronauts and Cosmonauts have also shown suggestive increases in urinary by-products of mineralized and non-mineralized tissue degradation. Thus, the idea of assessing connective tissue and bone response in spaceflight monkeys by measurement of biomarkers in urine has merit. Other investigations of bone and connective histology, cytology and chemistry in the Bion 11 monkeys will allow for further validation of the relationship of urinary biomarkers and tissue response. In future flights the non-invasive procedure of urinary analysis may be useful in early detection of changes in these tissues. *Purpose:* The purpose of this grant investigation was to evaluate mineralized and non-mineralized connective tissue responses of non-human primates to microgravity by the non-invasive analysis of urinary biomarkers. Secondly, we also wanted to assess muscle connective tissue adaptive changes in three weight-bearing skeletal muscles: the soleus, medial gastrocnemius and tibialis anterior by obtaining pre-flight and post-flight small biopsy specimens in collaboration with Dr. V. Reggie Edgerton's laboratory at the University of California at Los Angeles.

METHODS

Twenty-four hour samples were obtained intermittently before flight and after flight, before and after 1 G simulations of flight, and from vivarium monkeys. Urine volumes were measured and aliquots were frozen for subsequent analysis.

Collagen biomarker concentrations of urinary hydroxyproline (Hyp), hydroxylysylpyridinoline (HP cross-links), and lysylpyridinoline (LP cross-links) were assayed by reverse-phase high performance liquid chromatography (RP-HPLC).

Urinary creatinine (Cr) was quantitated using a colorimetric assay to measure potential muscle rhabdomyolysis and to normalize the connective tissue and bone mineral bio-marker concentrations.

Bone mineral metabolism was analyzed by assaying pre- and post-flight urinary calcium (Ca^{2+}) by atomic absorption. Urinary osteocalcin (Oc), a biomarker for bone formation was analyzed by immunoassay with a polyclonal antibody raised against bovine Oc with tracer and standards derived from purified *Macaca mulatta* bone Oc.

Skeletal muscle hydroxyproline, an index of collagen concentration, and the mature collagen cross-links (HP and LP) were measured on micro-biopsy specimens from the pre-flight and post-flight time periods from all three groups.

Statistics: The urine measurements were analyzed using a two factorial repeated measures analyses of variance (ANOVA) with the significance set at $P < 0.05$.

RESULTS

Collagen Biomarkers: Summary Tables (Pre-Flight and Post-Flight) and Graphs (Pre-Post, Monthly and Daily Analyses) can be found in the appropriate sections.

Results indicate a high daily variance in the urine concentration of collagen metabolic biomarkers. The urinary collagen cross-link content in the postflight urines were significantly greater ($P < 0.05$) in the Flight group compared to the Simulation and Vivarium groups indicating that more mature collagen had been degraded during the initial postflight recovery period in the Flight group. Creatinine analyses showed that in all groups urinary levels were significantly elevated (92%-111%) from preflight and the urinary content of non-reducible collagen cross-links (nM HP+LP/mM Cr) were overall greater during the postflight period (21%-35%).

Bone metabolism: Urinary Ca^{2+} measures were significantly lower (Flight -72%, Simulation -57%, Vivarium -31%) after flight versus preflight measurements ($P < 0.05$). Oc analyses indicated that Flight (-43%) and Vivarium (-32%) had significantly lower Oc values postflight.

Muscle Connective Tissue: In the soleus muscle, the only significant changes observed were in the Vivarium group. The Hyp values were significantly greater post-flight versus preflight values ($P < 0.05$). There was a trend towards decreased LP values post-flight compared to pre-flight values

($P < 0.09$). No significant changes were found in the Flight or Simulated soleus muscle connective tissue measurements. In the tibialis anterior, the only significant differences were found in the Flight group. Post-flight Hyp was significantly smaller in the Flight group in contrast to pre-flight measurements ($P < 0.05$). However, HP and Total Cross-link measurements (HP+LP) tended to be larger post-flight compared to preflight measurements (HP: $P < 0.07$) and (HP+LP: $P < 0.09$) respectively. The medial gastrocnemius muscle demonstrated no significant differences in any measurements post-flight versus preflight ($P > 0.05$)

SUMMARY FINDINGS

1. Biomarker profiles can be used as a *first level* non-invasive analyses to determine if connective tissue metabolism has been altered following spaceflight. Initial postflight measurements of collagen and mineral biomarkers, demonstrated in the first days following flight in the Daily Graphs, suggest an increase in mineralized and non-mineralized connective tissue turnover in the Flight group.
2. Elevated urine Hyp, HP+LP cross-link levels together with reduced urine Ca^{2+} levels may indicate new collagen secretion and Ca^{2+} storage, signifying new bone formation during postflight recovery.
3. Biomarker analyses investigating the temporal transitions of whole body collagen and mineral metabolism would be greatly enhanced if future experiments facilitated daily in-flight sample collection of urine from the primates aboard the unmanned space habitat.
4. Overall, no dramatic muscle connective tissue changes were observed post-flight in the SOL, MG or TA muscles. However, there was a significant decrease in skeletal muscle collagen in the post-flight TA biopsies in the Flight group with an accompanying increase in muscle collagen cross-

linking suggesting that the interstitial collagen is older "more mature" collagen. This findings were not observed in the SOL or MG muscle biopsies.

5. Fourteen days exposure to microgravity may not have been an adequate interval of time to view changes in skeletal muscle connective tissue protein. However, changes at the molecular level of collagen synthesis (measures of mRNA for COL 1A1, COL 3A1 and Lysyl Oxidase) may be evident when analyzed.
6. The biopsy samples received from Dr. Reggie Edgerton's laboratory were smaller in mass than what our current molecular biology methodology could quantitate. If our Laboratory receives further funding, we will attempt to optimize our mRNA assays for less than ~0.5-2.0 mg tissue wet weight.

TABLES

Pre-Flight and Post-Flight Urine Biomarker Analyses (Normalized to Creatinine)

Groups	Samples Collected	Hyp/Cr ($\mu\text{g}/\text{mMol}$)	HP/Cr (nMol/mMol)	LP/Cr (nMol/mMol)	Total Cross-links ($\text{nmol HP+LP}/\text{mmol Cr}$)
Flight (357,484) n = 2 <small>(1 sample collected from 357 post-flight: pooled with 484 post flight)</small>	Pre-flight (12-14)	19.89 \pm 2.29 ^a	120.51 \pm 13.90 ^a	21.01 \pm 2.86 ^{ab}	141.53 \pm 16.58 ^{ab}
	Post-flight (22)	17.39 \pm 2.92 ^a	146.03 \pm 6.56 ^a	25.45 \pm 1.52 ^a	171.49 \pm 7.89 ^a
Simulated (501,513,534) n = 3	Pre-flight (20-22)	9.66 \pm 1.02 ^b	82.68 \pm 6.21 ^b	15.74 \pm 2.56 ^{bc}	98.41 \pm 7.73 ^c
	Post-flight (30-36)	9.14 \pm 0.97 ^b	112.48 \pm 12.76 ^a	17.32 \pm 1.92 ^b	133.09 \pm 14.01 ^{ab}
Vivarium (396,447,448, 470,474,503) n = 6	Pre-flight (41-45)	10.11 \pm 0.59 ^b	86.24 \pm 4.69 ^b	11.74 \pm 0.71 ^c	97.97 \pm 5.33 ^c
	Post-flight (50-52)	8.77 \pm 0.39 ^b	110.67 \pm 8.59 ^a	16.66 \pm 1.30 ^b	127.32 \pm 9.82 ^b

Values represent means \pm SE. Means with the same letter are *not* significantly different. A significant *P* value was set at *P*<0.05.

Pre-Flight and Post-Flight Urine Biomarker Analyses (Non-normalized to Creatinine)

Groups	Samples Collected	Hyp (µg/mL)	HP (nM)	LP (nM)	Creatinine (mM)
Flight (357,484) n = 2 (1 sample collected from 357 post-flight; pooled with 484 post flight)	Pre-flight (12-14)	58.77±8.81 ^{bcd}	388.48±68.98 ^c	67.79±11.83 ^{cd}	3.67±0.72 ^b
	Post-flight (22)	85.11±13.44 ^a	1020.0±209.29 ^{ab}	649.67±102.62 ^{ab}	7.76±1.83 ^a
Simulated (501,513,534) n = 3	Pre-flight (20-22)	38.27±5.78 ^c	359.25±52.81 ^c	61.29±7.86 ^{cd}	4.13±0.54 ^b
	Post-flight (30-36)	57.22±5.69 ^{bcd}	710.47±88.91 ^{ac}	111.56±13.96 ^{ac}	8.31±0.96 ^a
Vivarium (396,447,448,470,474,503) n = 6	Pre-flight (41-45)	43.49±3.98 ^c	396.39±47.08 ^c	54.62±7.16 ^d	4.66±0.37 ^b
	Post-flight (50-52)	64.13±5.62 ^{ad}	1083.82±195.10 ^b	169.98±30.07 ^b	8.95±1.15 ^a

Values represent means ± SE. Means with the same letter are *not* significantly different. A significant *P* value was set at *P*<0.05.

Urinary Calcium and Osteocalcin

Pre-Flight and Post-Flight Analyses

Groups	Time (# of samples)	Calcium (Ca ²⁺ µg/mg Creatinine)	Osteocalcin (ng OC/ mg Creatinine)
Flight (357,484) n = 2	Pre-flight (n)	49.4±13.7 ^a (15)	2.44±0.45 ^a (10)
	Post-flight (n)	18.9±3.9 ^b (23)	1.39±0.24 ^b (21)
Simulated (501,513,534) n = 3	Pre-flight (n)	52.5±16.2 ^a (23)	1.09±0.22 ^a (7)
	Post-flight (n)	22.8±4.5 ^b (23)	3.25±0.93 ^a (28)
Vivarium (396,447,448, 470,474,503) n = 6	Pre-flight (n)	37.3±6.0 ^a (45)	2.60±0.86 ^a (2)
	Post-flight (n)	25.9±3.3 ^a (52)	1.76±0.47 ^a (13)

Values represent means ± SE. Means with the same letter are *not* significantly different. A significant *P* value was set at *P*<0.05. ^aFlight Group Postflight Ca²⁺ (*P*<0.02) and OC (*P*<0.03) are significantly less than Preflight values. ^bSimulated Group Postflight Ca²⁺ (*P*<0.05) is significantly less than Preflight values.

Soleus Pre-Flight and Post-Flight Biopsies

Muscle Connective Tissue Analyses

Groups	Time	Hyp ($\mu\text{g}/\text{mg}$ dry wt)	HP (mol HP/mol Collagen)	LP (mol LP/mol Collagen)	Total Cross-links (HP+LP)
Flight (357,484) n = 2	Pre-flight	5.34 \pm 0.26 ^a	0.4361 \pm 0.154 ^a	0.0727 \pm 0.283 ^a	0.5088 \pm 0.182 ^a
	Post-flight	10.92 \pm 3.49 ^a	0.3897 \pm 0.128 ^a	0.0529 \pm 0.005 ^a	0.4426 \pm 0.132 ^a
Simulated (501,513,534) n = 3	Pre-flight	6.06 \pm 1.82 ^a	0.4940 \pm 0.075 ^a	0.0690 \pm 0.024 ^a	0.5629 \pm 0.098 ^a
	Post-flight	11.76 \pm 4.30 ^a	0.6709 \pm 0.292 ^a	0.1099 \pm 0.051 ^a	0.7809 \pm 0.343 ^a
Vivarium (396,447,448, 470,474,503) n = 6	Pre-flight	6.57 \pm 1.93 ^a	0.8439 \pm 0.428 ^a	0.1302 \pm 0.057 ^a	0.9741 \pm 0.485 ^a
	Post-flight	11.01 \pm 2.14 ^b	0.3667 \pm 0.050 ^a	0.0448 \pm 0.008 ^b	0.4115 \pm 0.058 ^a

Values represent means \pm SE. Means with the same letter are *not* significantly different.
^bVivarium Soleus Postflight Hyp (P<0.04) and LP (<0.09) values are significantly less than Preflight values.

Tibialis Anterior Pre-Flight and Post-Flight Biopsies

Muscle Connective Tissue Analyses

Groups	Time	Hyp ($\mu\text{g}/\text{mg}$ dry wt)	HP (mol HP/mol Collagen)	LP (mol LP/mol Collagen)	Total Cross-links (HP+LP)
Flight (357,484) n = 2	Pre-flight	10.49 \pm 6.53 ^a	0.2732 \pm 0.068 ^a	0.0337 \pm 0.011 ^a	0.3069 \pm 0.080 ^a
	Post-flight	1.68 \pm 0.15 ^b	0.8867 \pm 0.006 ^c	0.1153 \pm 0.017 ^a	1.003 \pm 0.011 ^c
Simulated (501,513,534) n = 3	Pre-flight	4.12 \pm 0.70 ^a	0.3441 \pm 0.024 ^a	0.0597 \pm 0.009 ^a	0.4039 \pm 0.027 ^a
	Post-flight	4.33 \pm 1.29 ^a	0.6101 \pm 0.227 ^a	0.1025 \pm 0.040 ^a	0.7126 \pm 0.268 ^a
Vivarium (396,447,448, 470,474,503) n = 6	Pre-flight	4.95 \pm 1.38 ^a	0.4374 \pm 0.178 ^a	0.0858 \pm 0.040 ^a	0.5232 \pm 0.217 ^a
	Post-flight	6.16 \pm 0.75 ^a	0.2695 \pm 0.030 ^a	0.0422 \pm 0.006 ^a	0.3117 \pm 0.034 ^a

Values represent means \pm SE. Means with the same letter are *not* significantly different. A significant *P* value was set at $P < 0.05$.
^bSoleus Postflight Hyp ($P < 0.03$) is significantly less than the Preflight values. ^cSoleus Postflight HP ($P < 0.07$) and HP+LP ($P < 0.09$) values are significantly greater than Preflight values.

Medial Gastrocnemius Pre-Flight and Post-Flight Biopsies

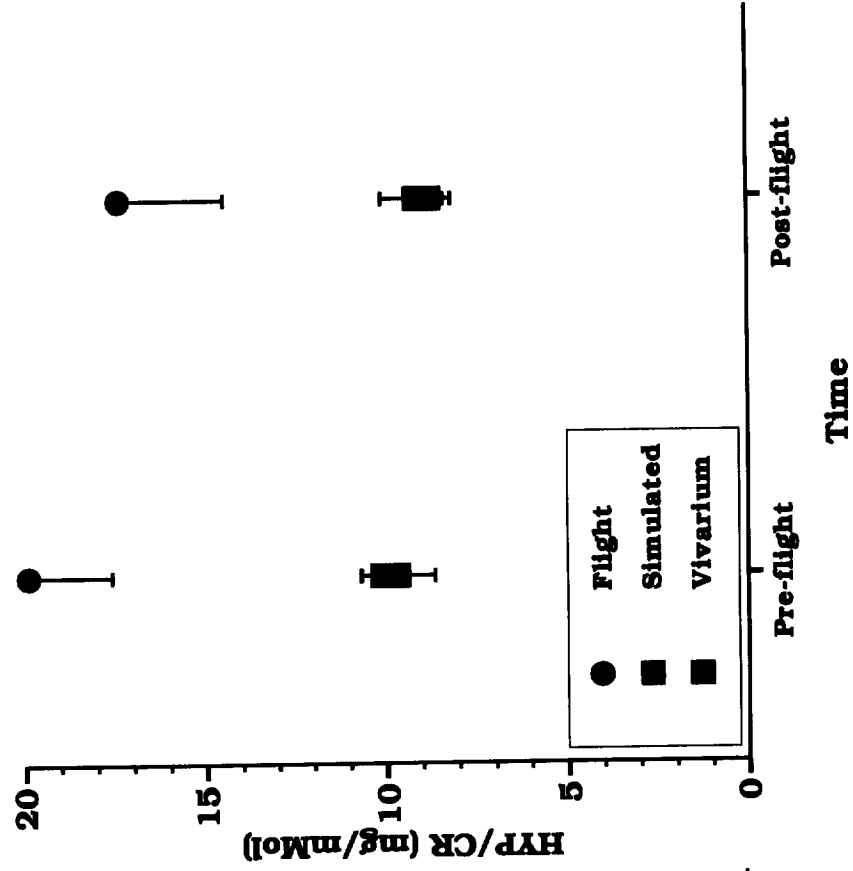
Muscle Connective Tissue Analyses

Groups	Time	Hyp ($\mu\text{g}/\text{mg}$ dry wt)	HP (mol HP/mol Collagen)	LP (mol LP/mol Collagen)	Total Cross-links (HP+LP)
Flight (357,484) n = 2	Pre-flight	3.07 \pm 0.05	0.6561 \pm 0.120	0.0810 \pm 0.041	0.7371 \pm 0.161
	Post-flight	7.75 \pm 6.46	0.4849 \pm 0.289	0.0624 \pm 0.035	0.5473 \pm 0.324
Simulated (501,513,534) n = 3	Pre-flight	4.48 \pm 1.54	0.4720 \pm 0.184	0.0552 \pm 0.157	0.5272 \pm 0.199
	Post-flight	3.93 \pm 1.59	0.8010 \pm 0.347	0.1214 \pm 0.079	0.9225 \pm 0.391
Vivarium (396,447,448, 470,474,503) n = 6	Pre-flight	5.64 \pm 1.14	0.4774 \pm 0.172	0.0870 \pm 0.038	0.5644 \pm 0.209
	Post-flight	6.36 \pm 0.98	0.3395 \pm 0.060	0.0473 \pm 0.008	0.3868 \pm 0.067

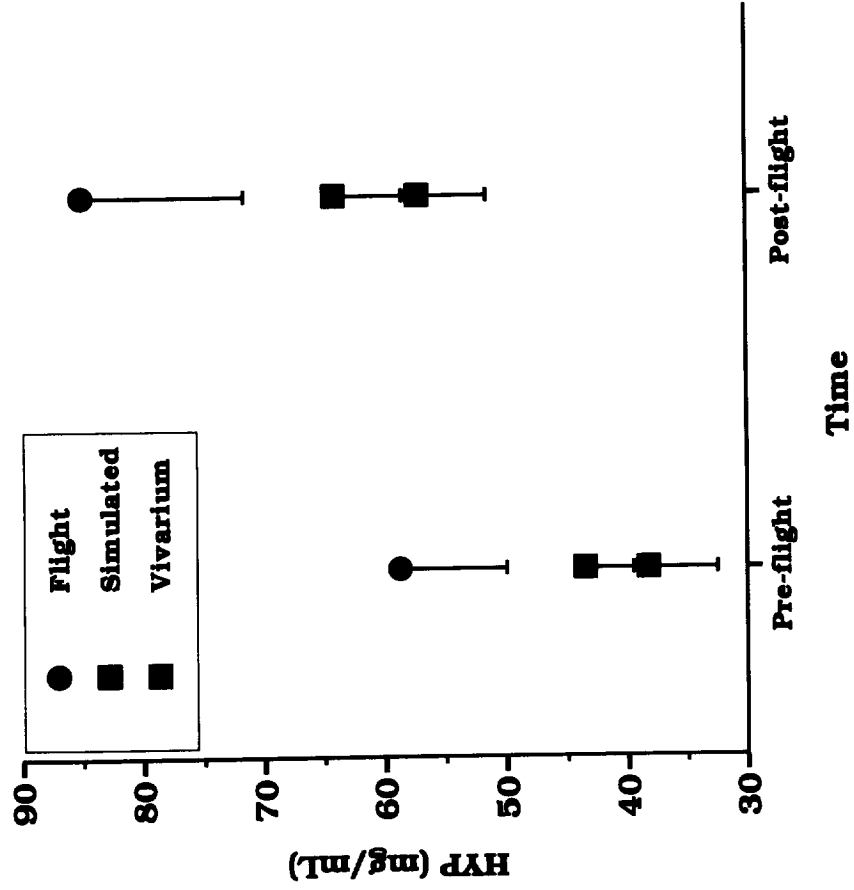
Values represent means \pm SE. Means with the same letter are *not* significantly different. There are no significant differences between Groups ($P > 0.05$)

FIGURES

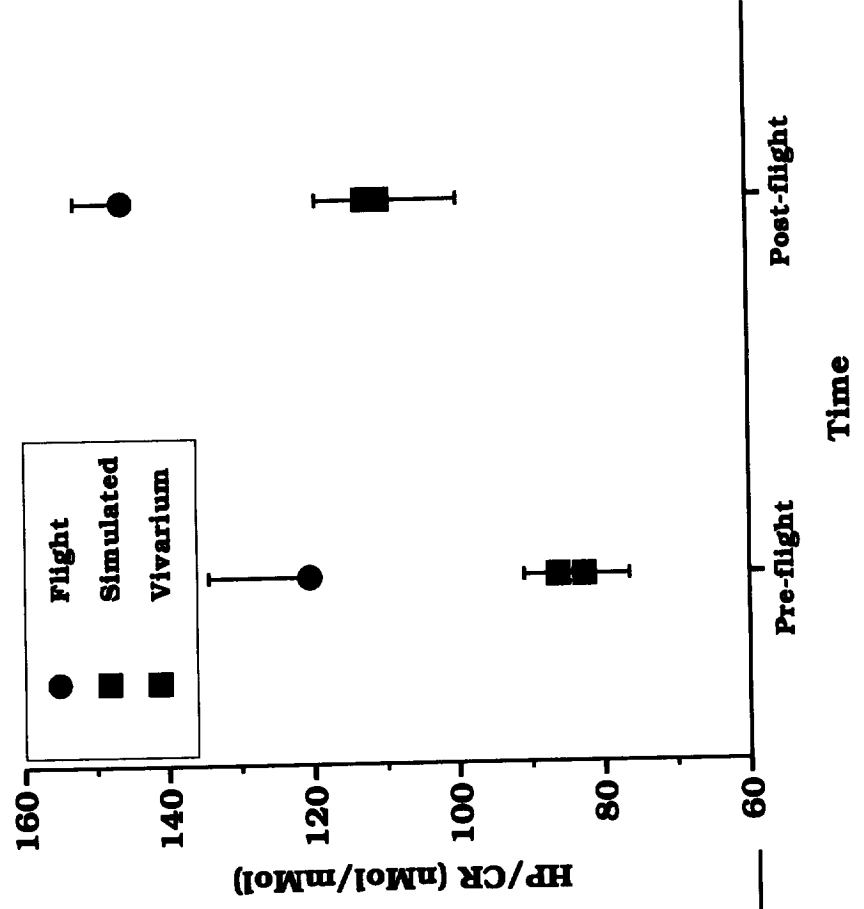
HYP/CR values for the 3 Animal Groups



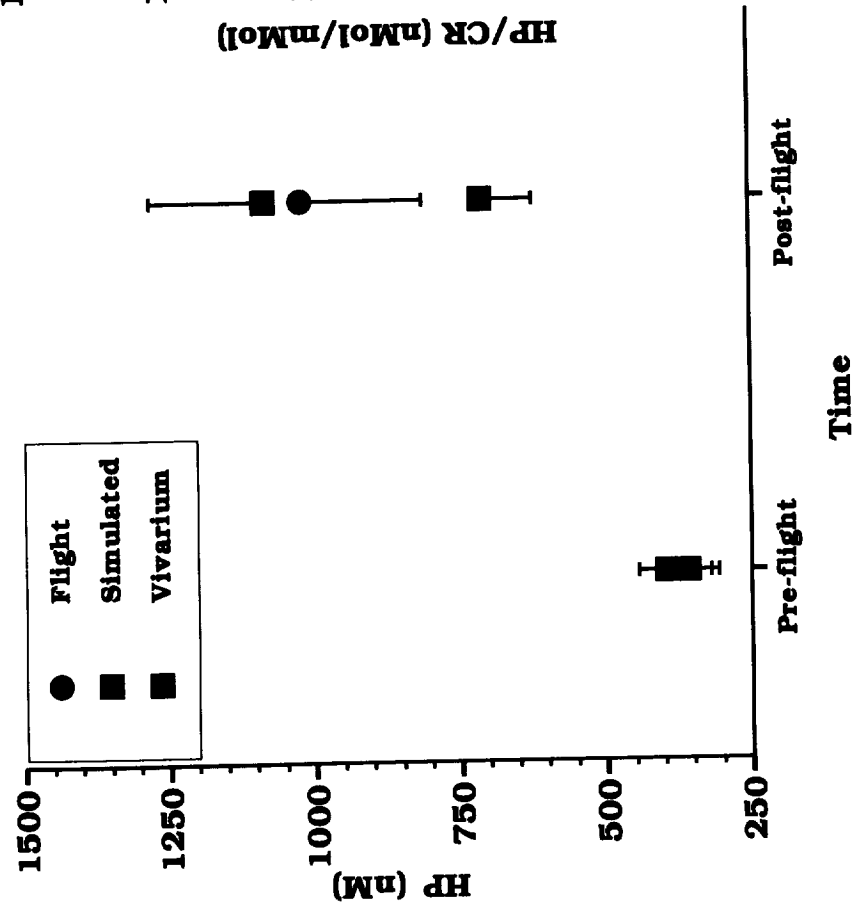
HYP values for the 3 Animal Groups



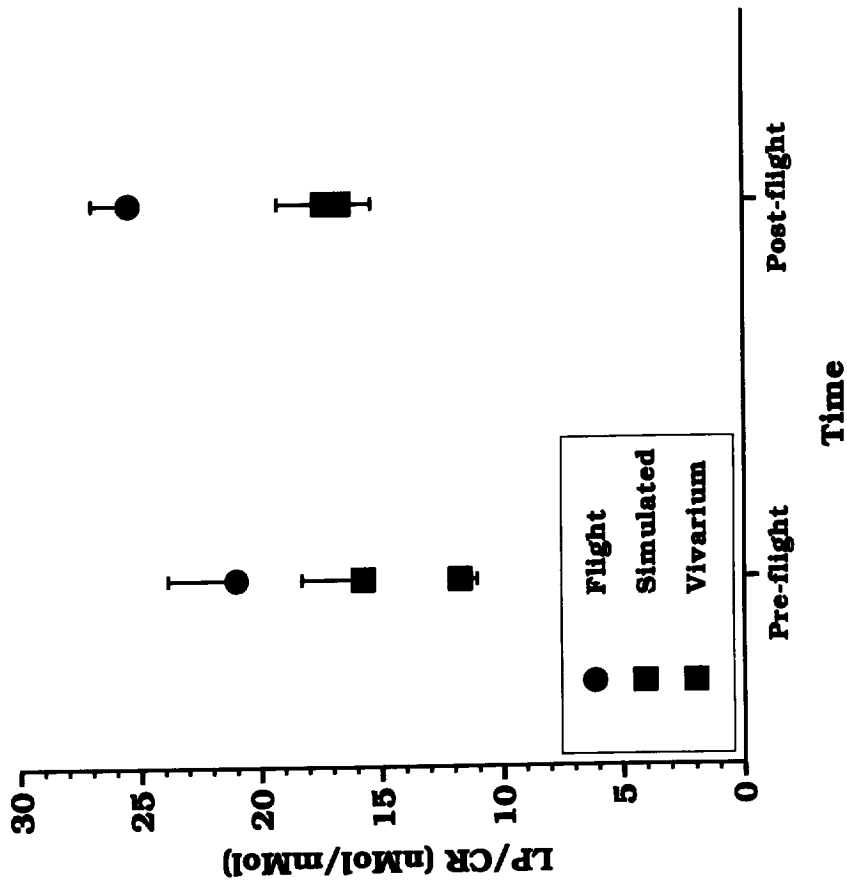
HP/CR values for the 3 Animal Groups



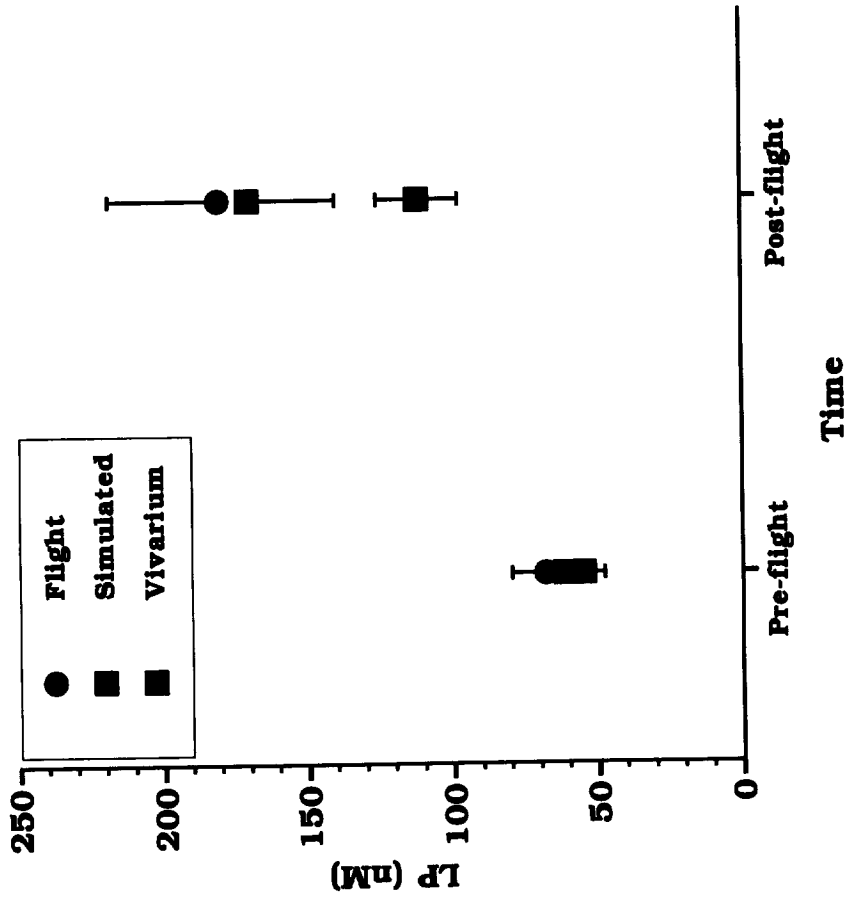
HP values for the 3 Animal Groups



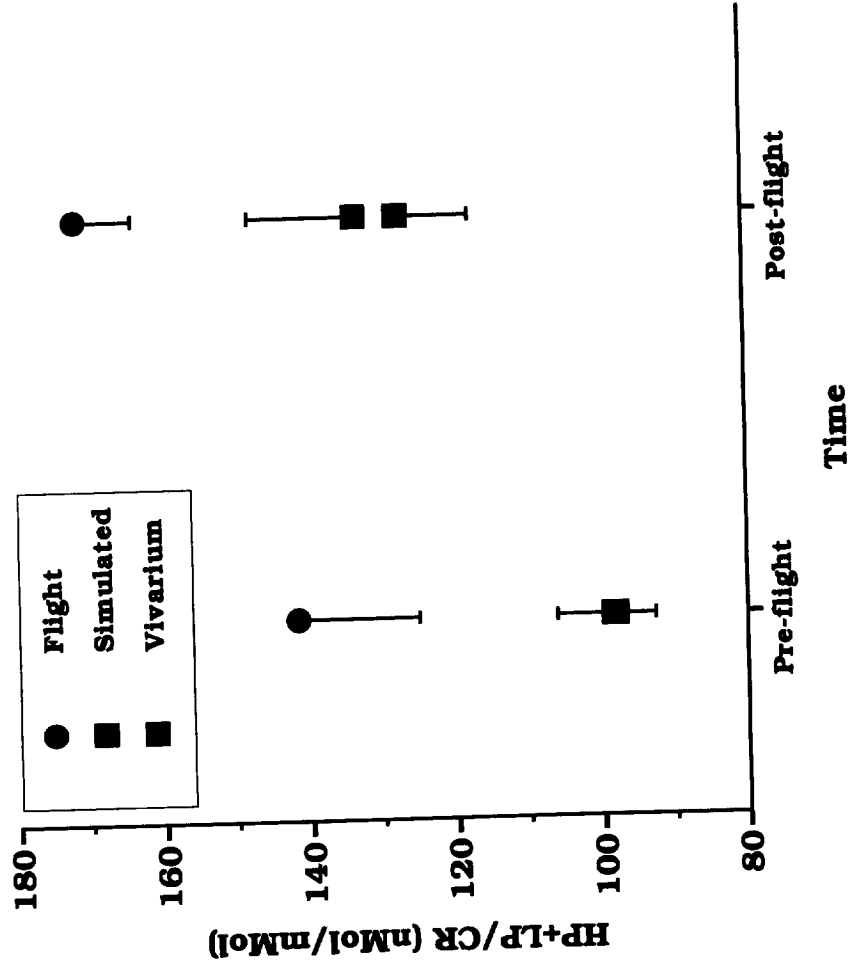
LP/CR values for the 3 Animal Groups



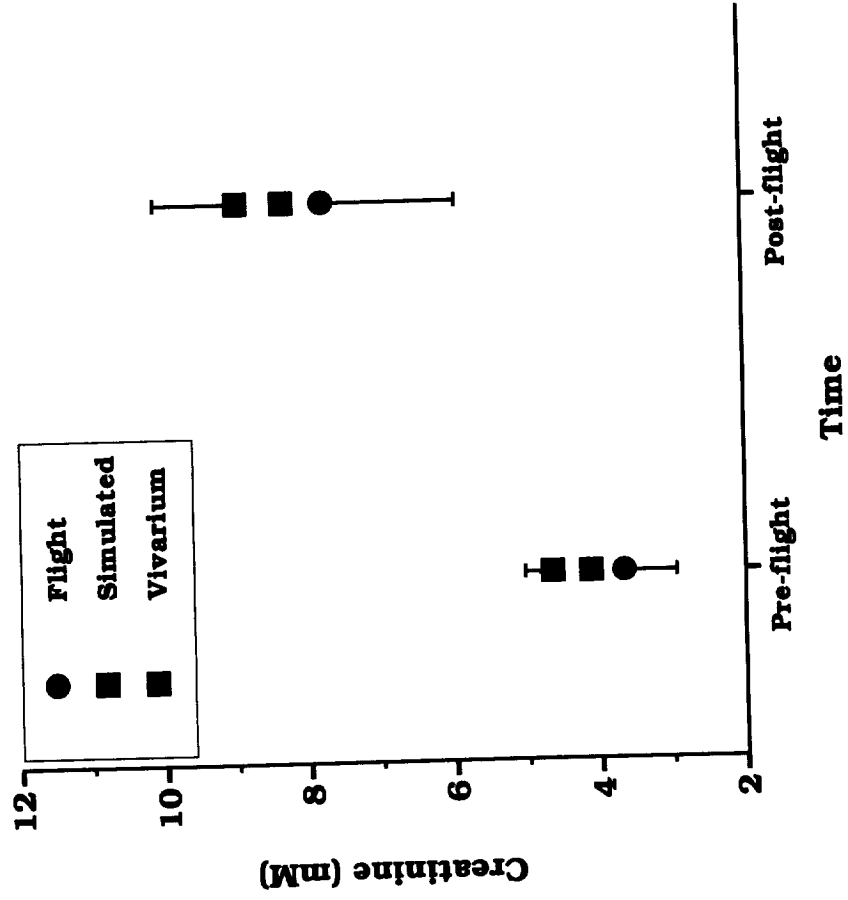
LP values for the 3 Animal Groups



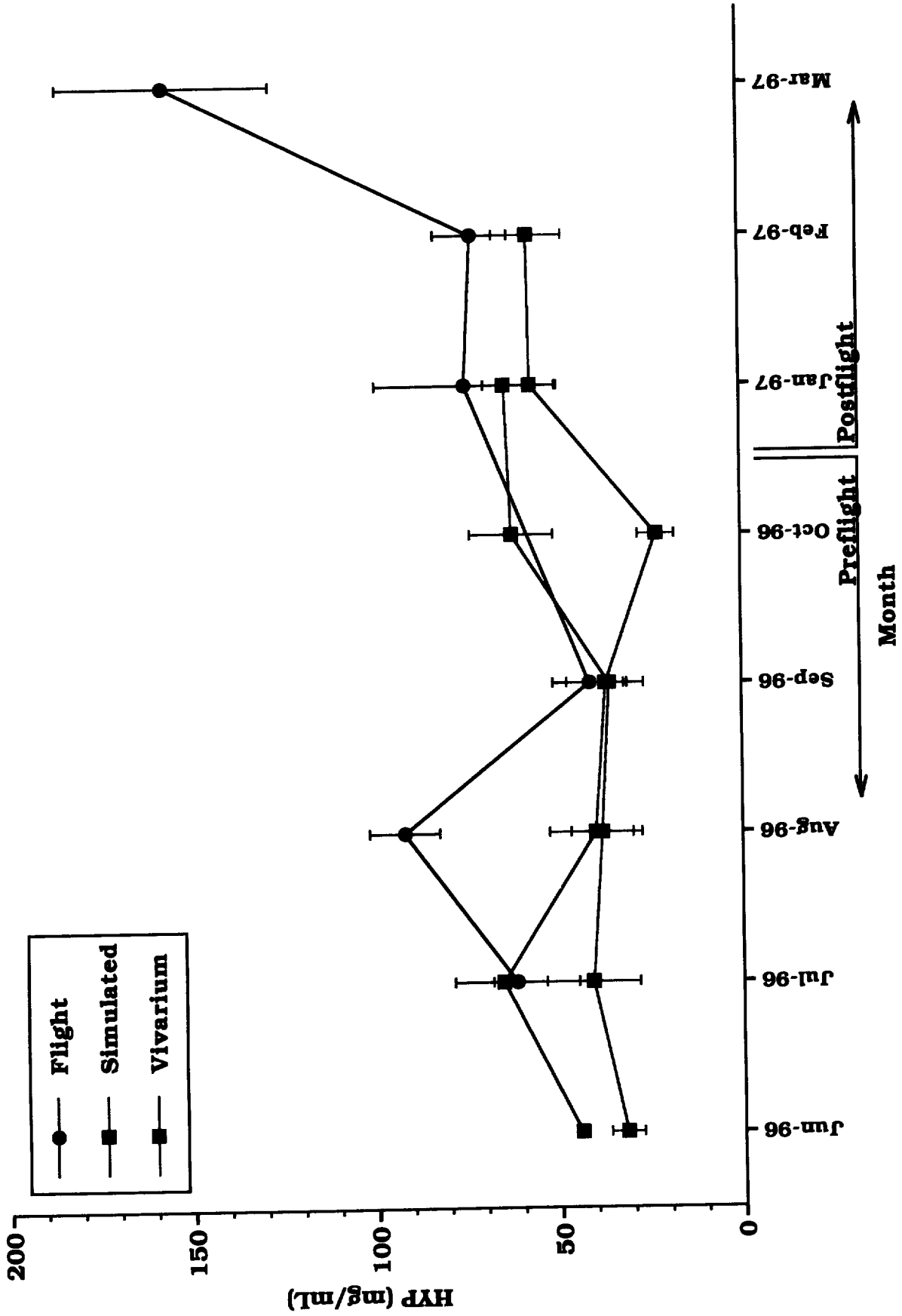
Total Collagen Cross-links (HP+LP/CR)



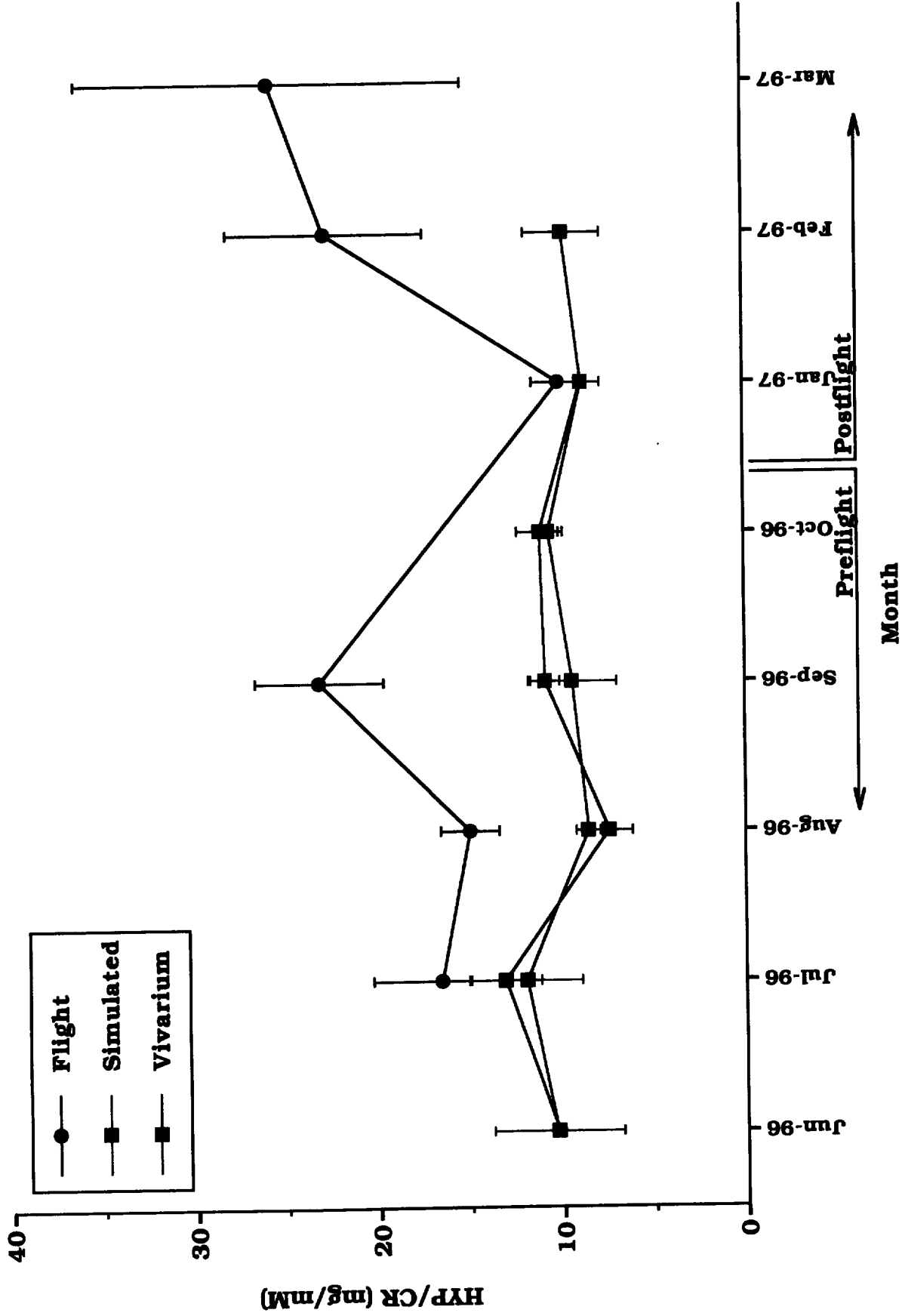
Creatinine values for the 3 animal groups



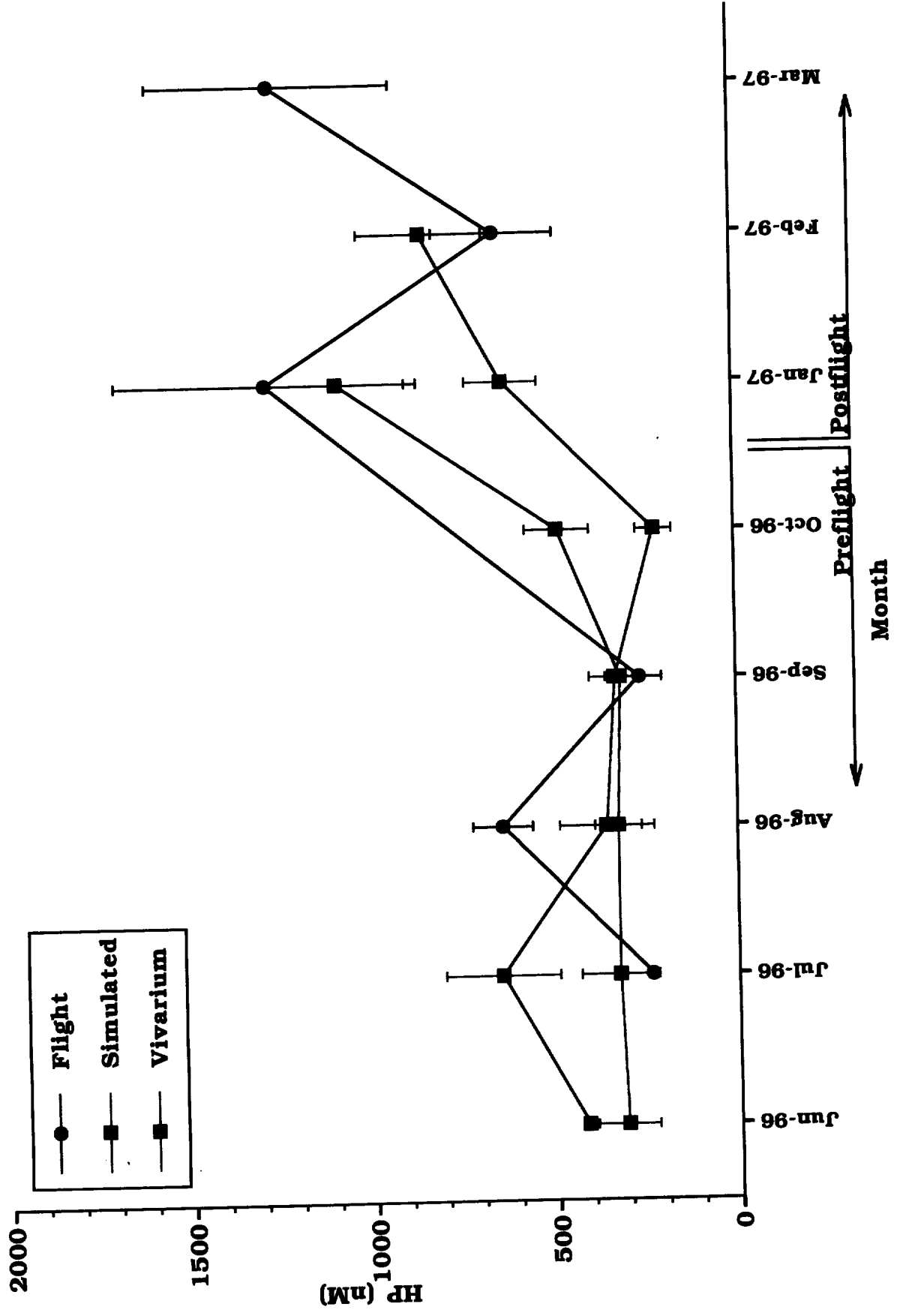
Monthly HYP values for the 3 Animal Groups



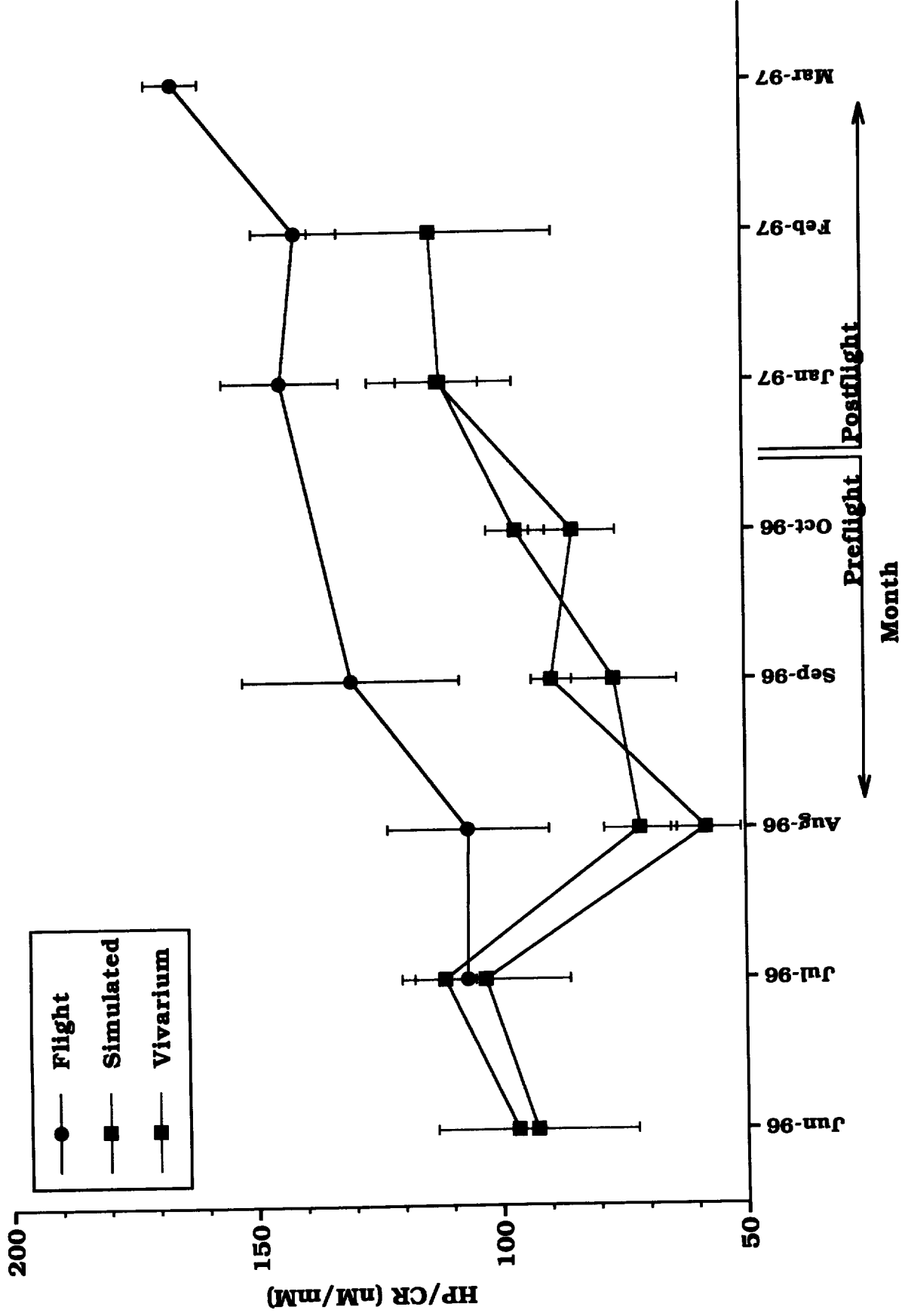
Monthly HYP/CR values for the 3 Animal Groups



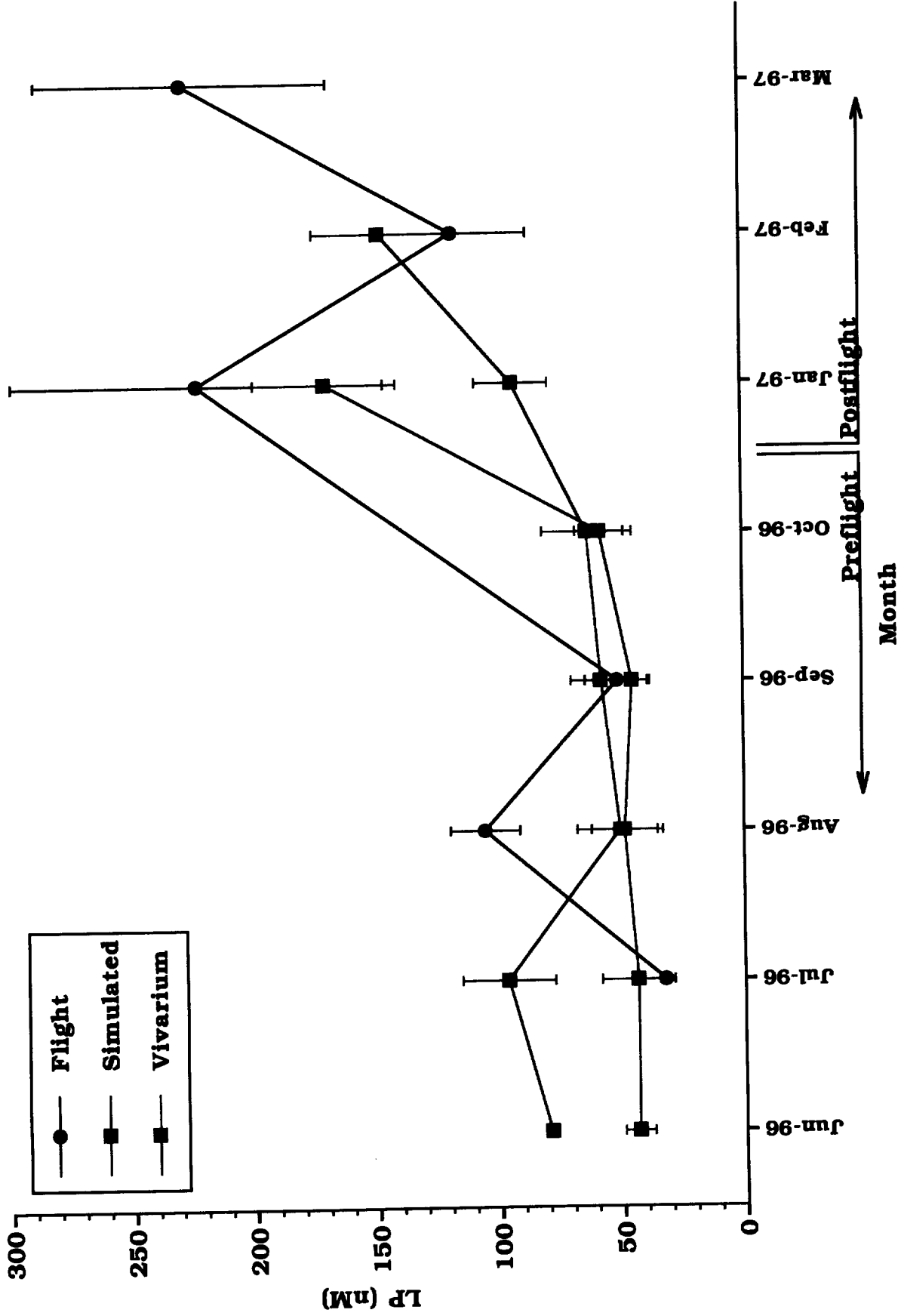
Monthly HP values for the 3 Animal Groups



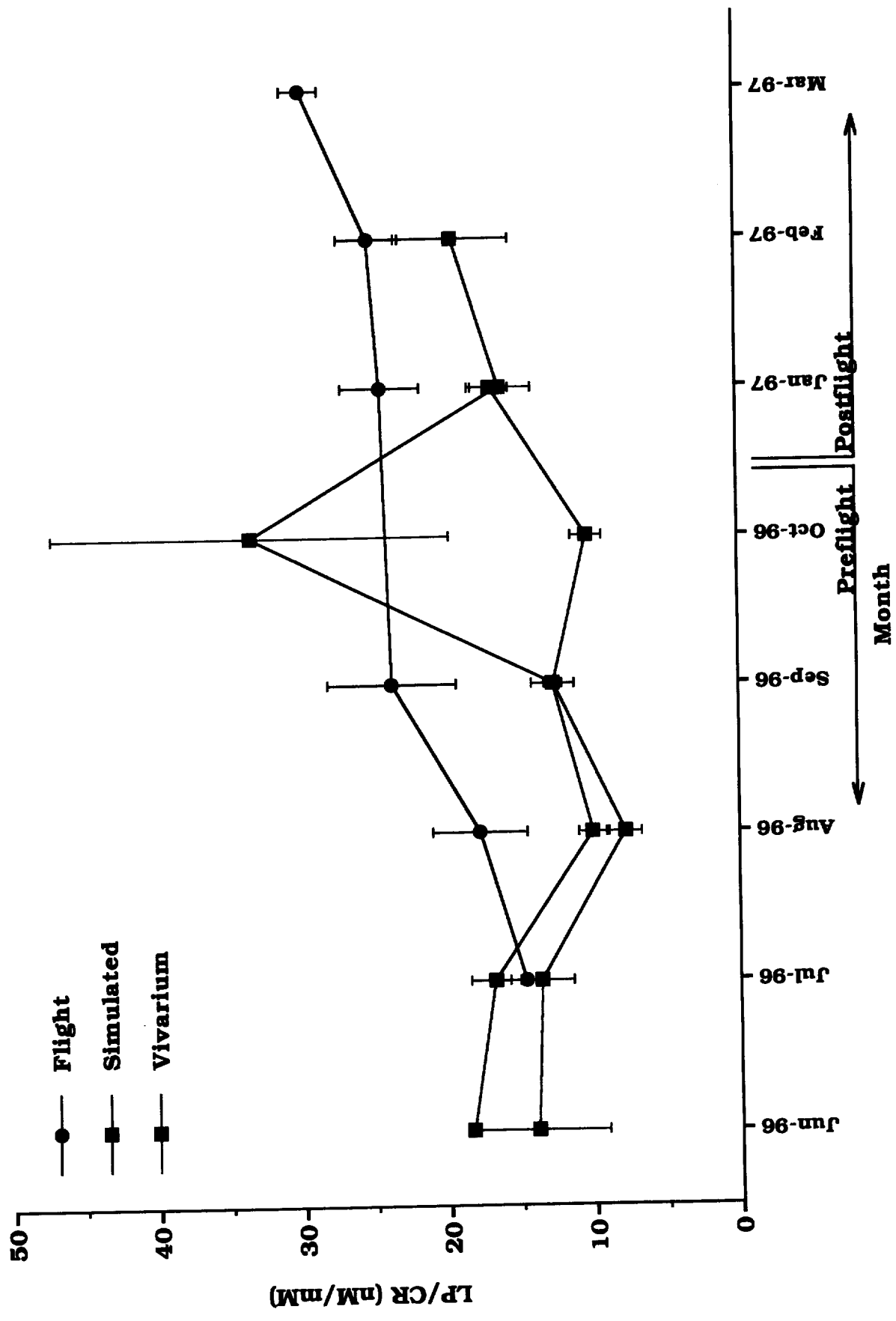
Monthly HP/CR values for the 3 Animal Groups



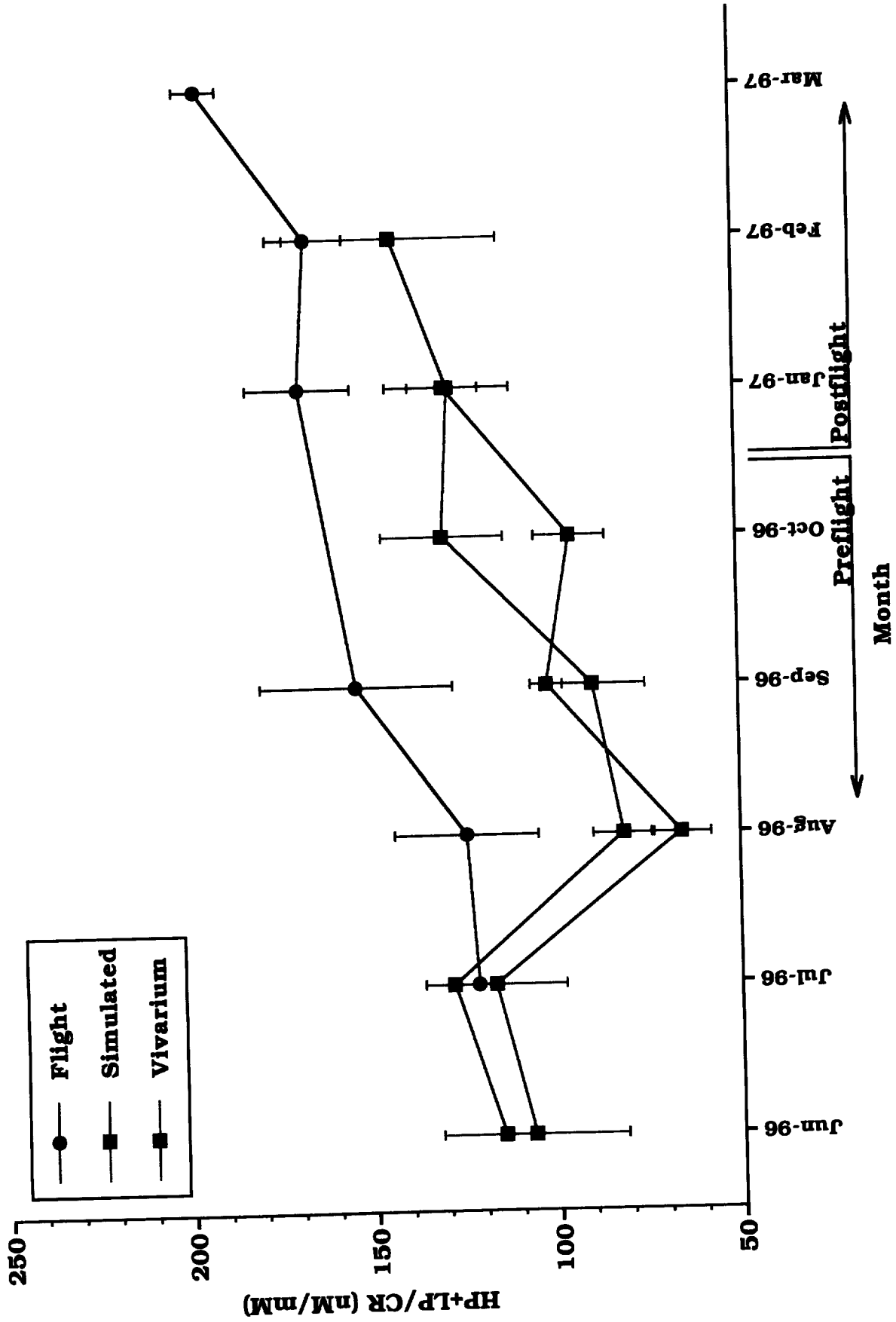
Monthly LP values for the 3 Animal Groups



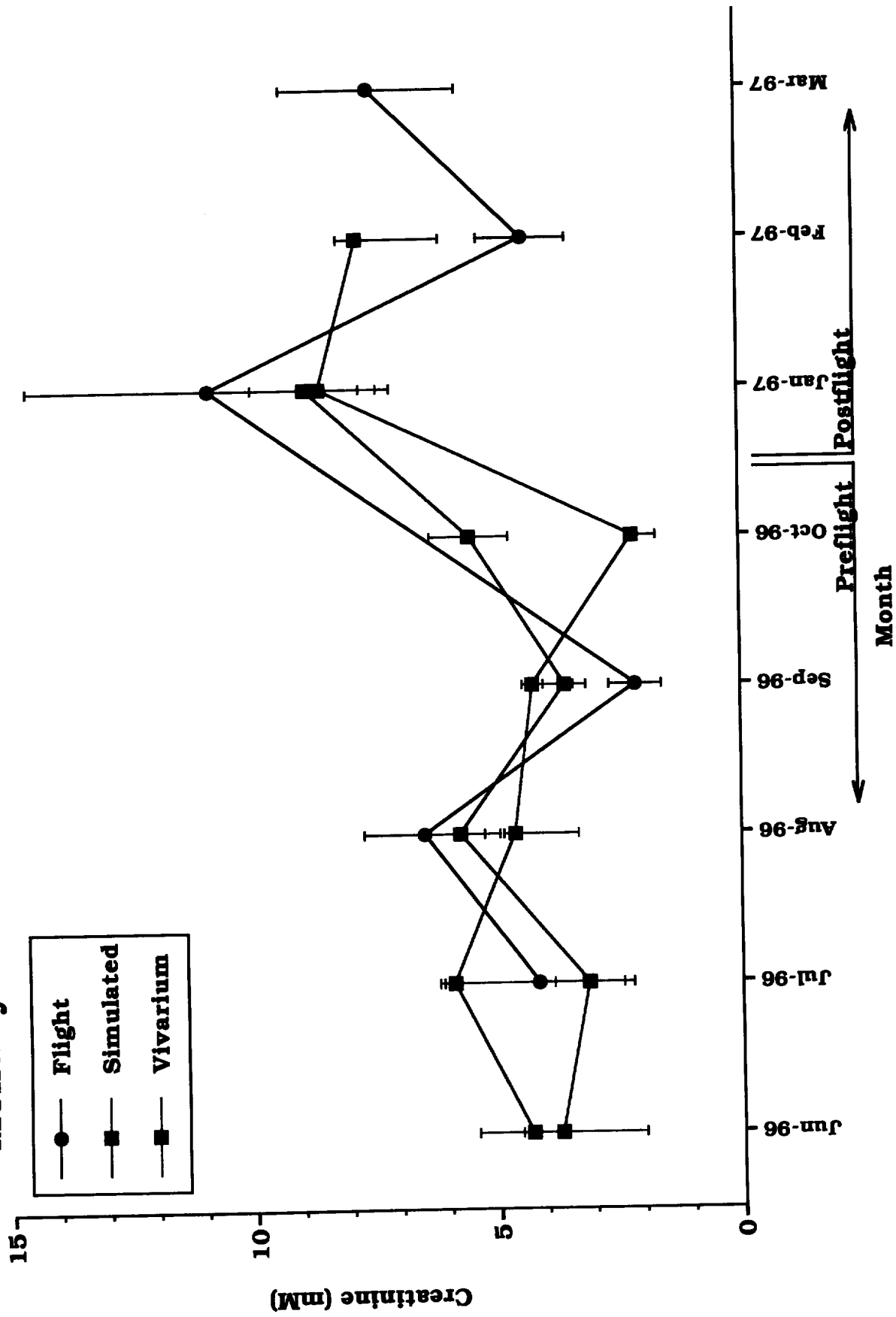
Monthly LP/CR values for the 3 Animal Groups



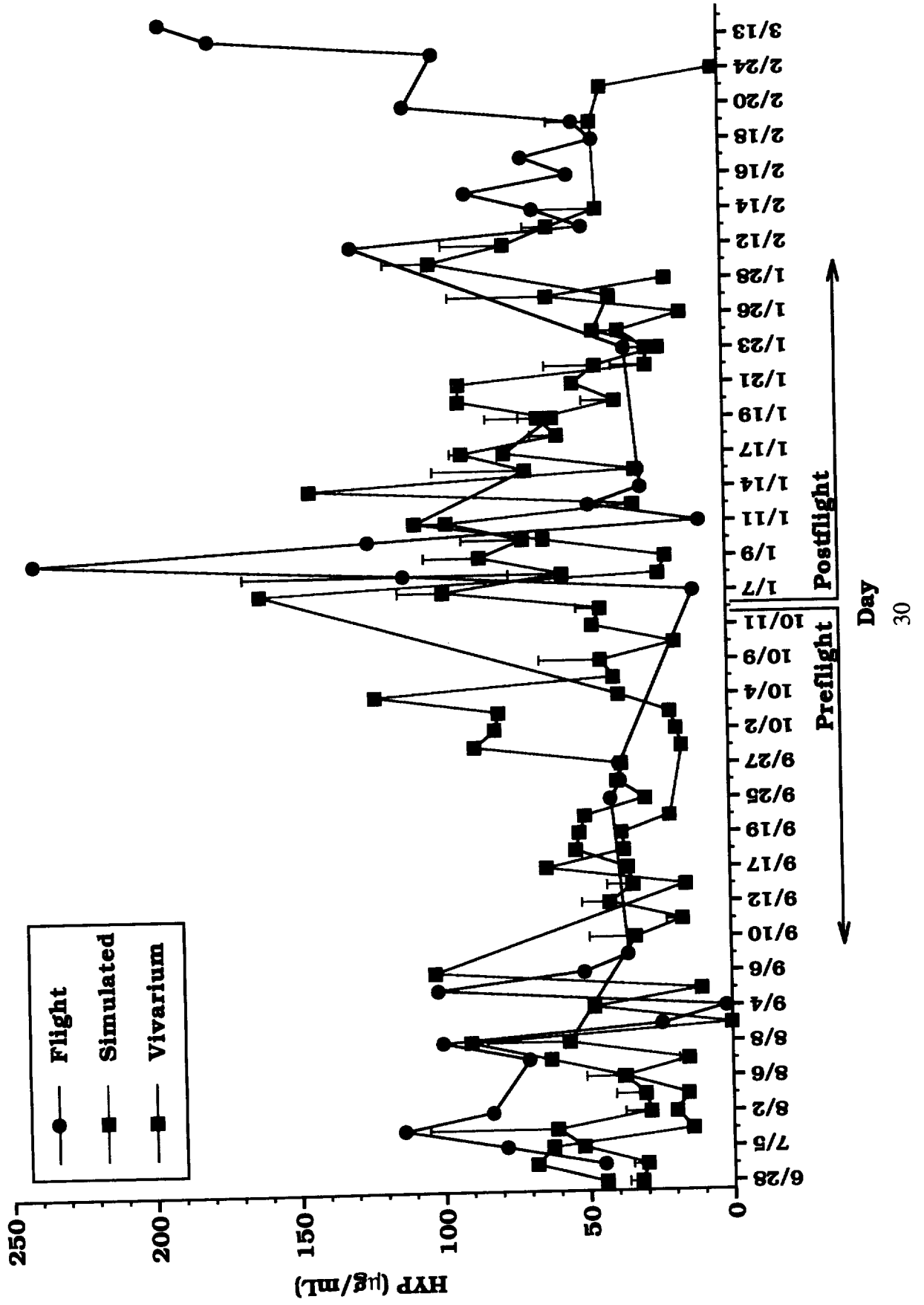
Monthly HP+LP/CR values for the 3 Animal Groups



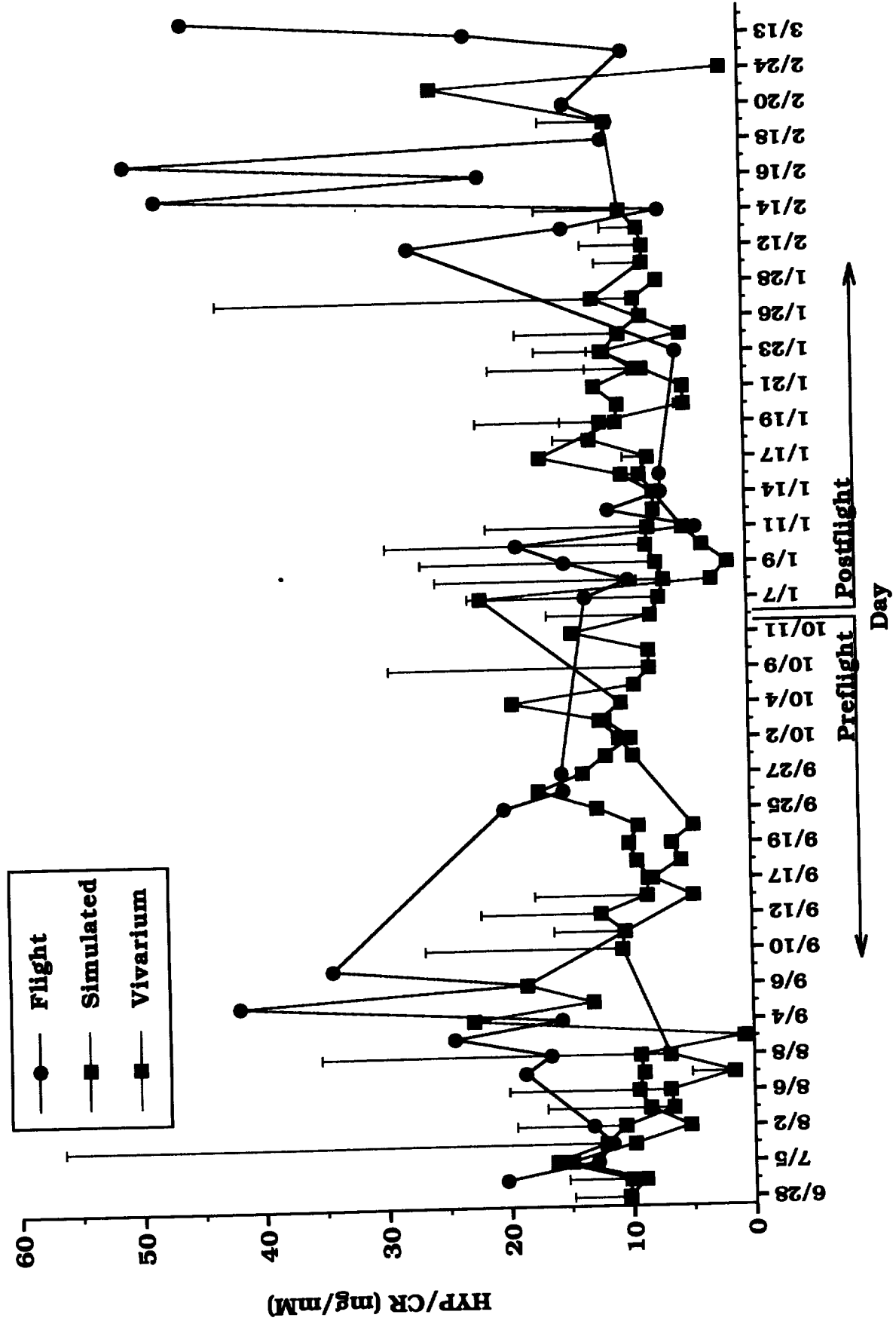
Monthly Creatinine values for the 3 Animal Groups



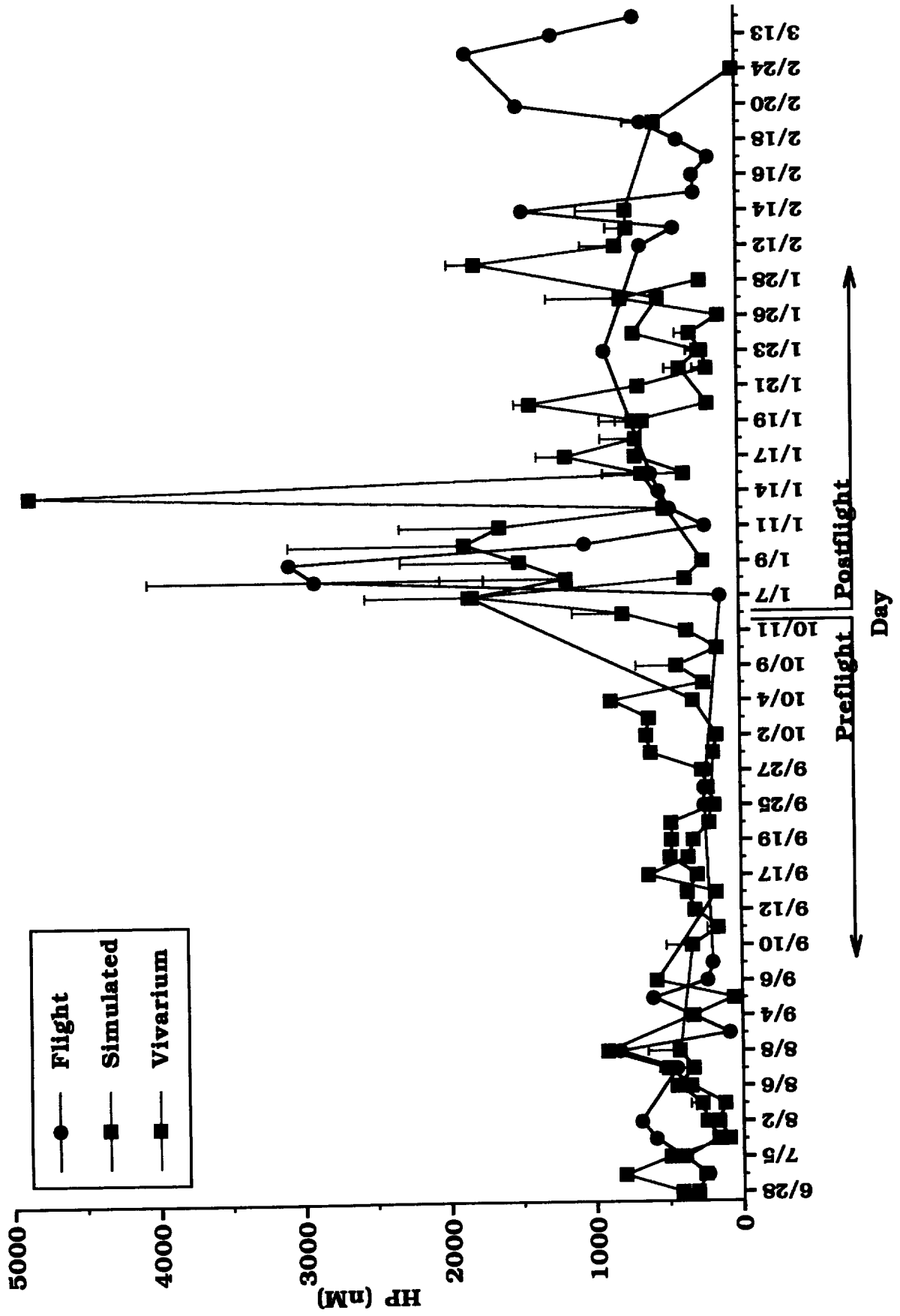
Daily HYP values for the 3 Animal Groups



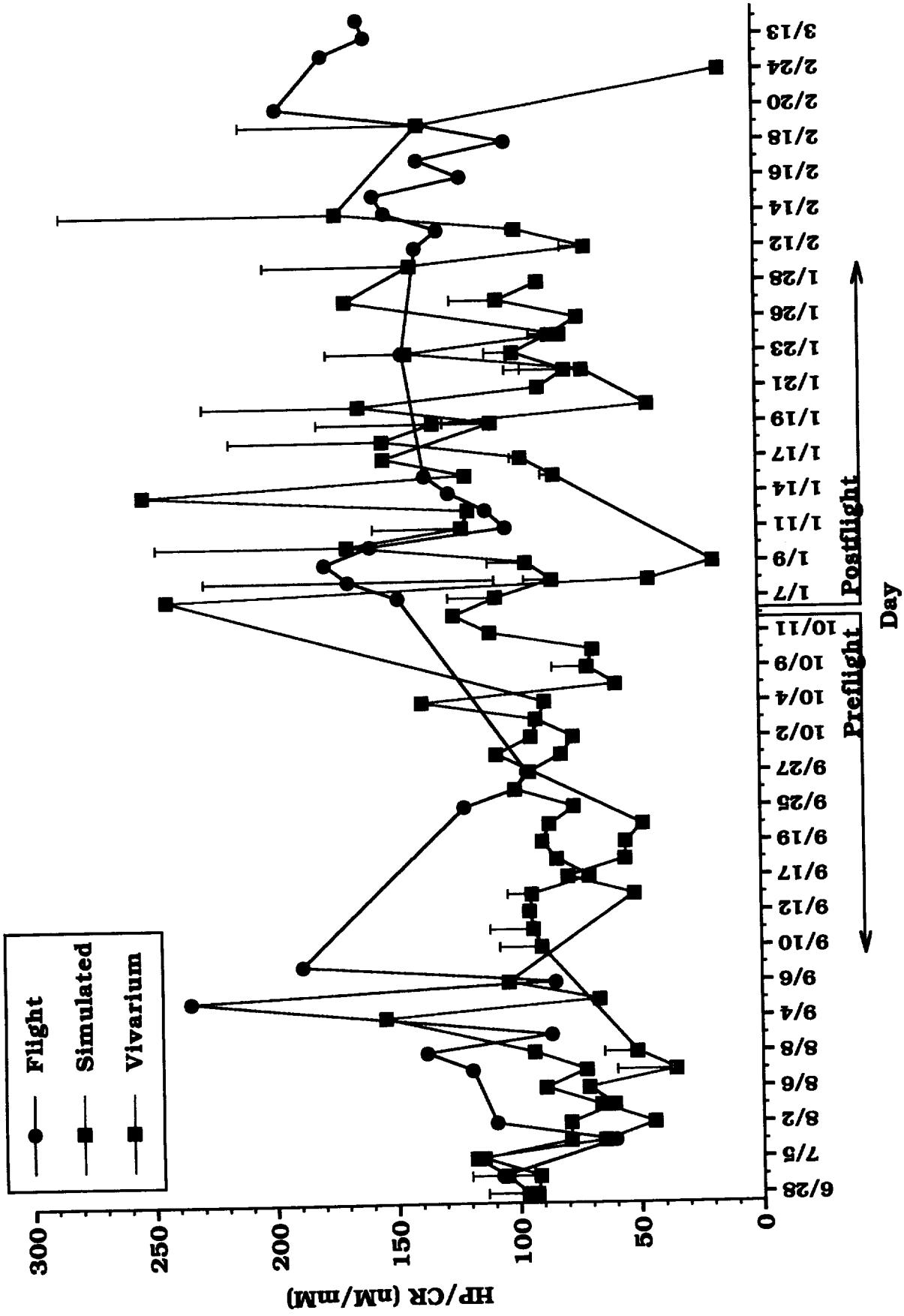
Daily HYP/CR values for the 3 Animal Groups



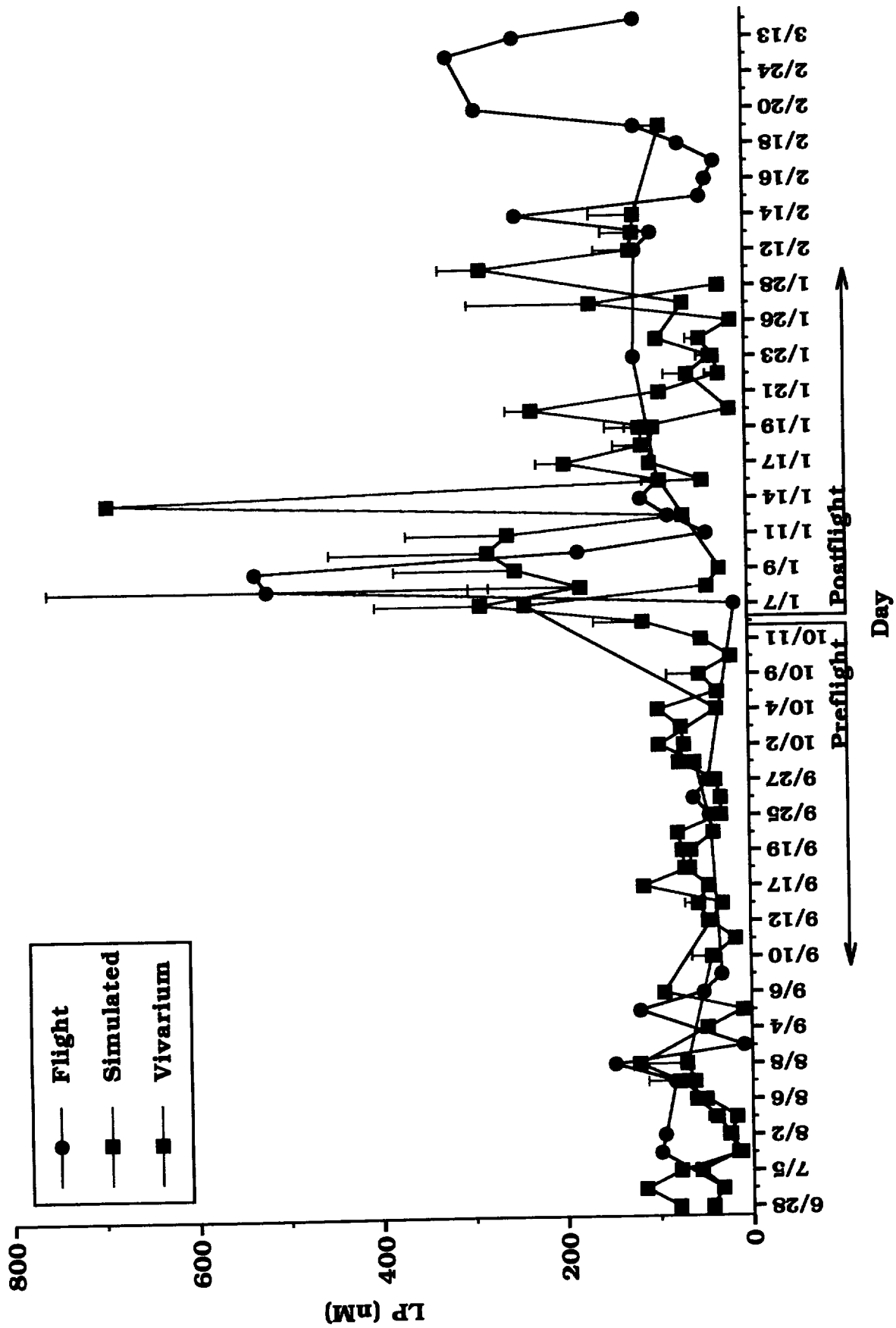
Daily HP values for the 3 Animal Groups



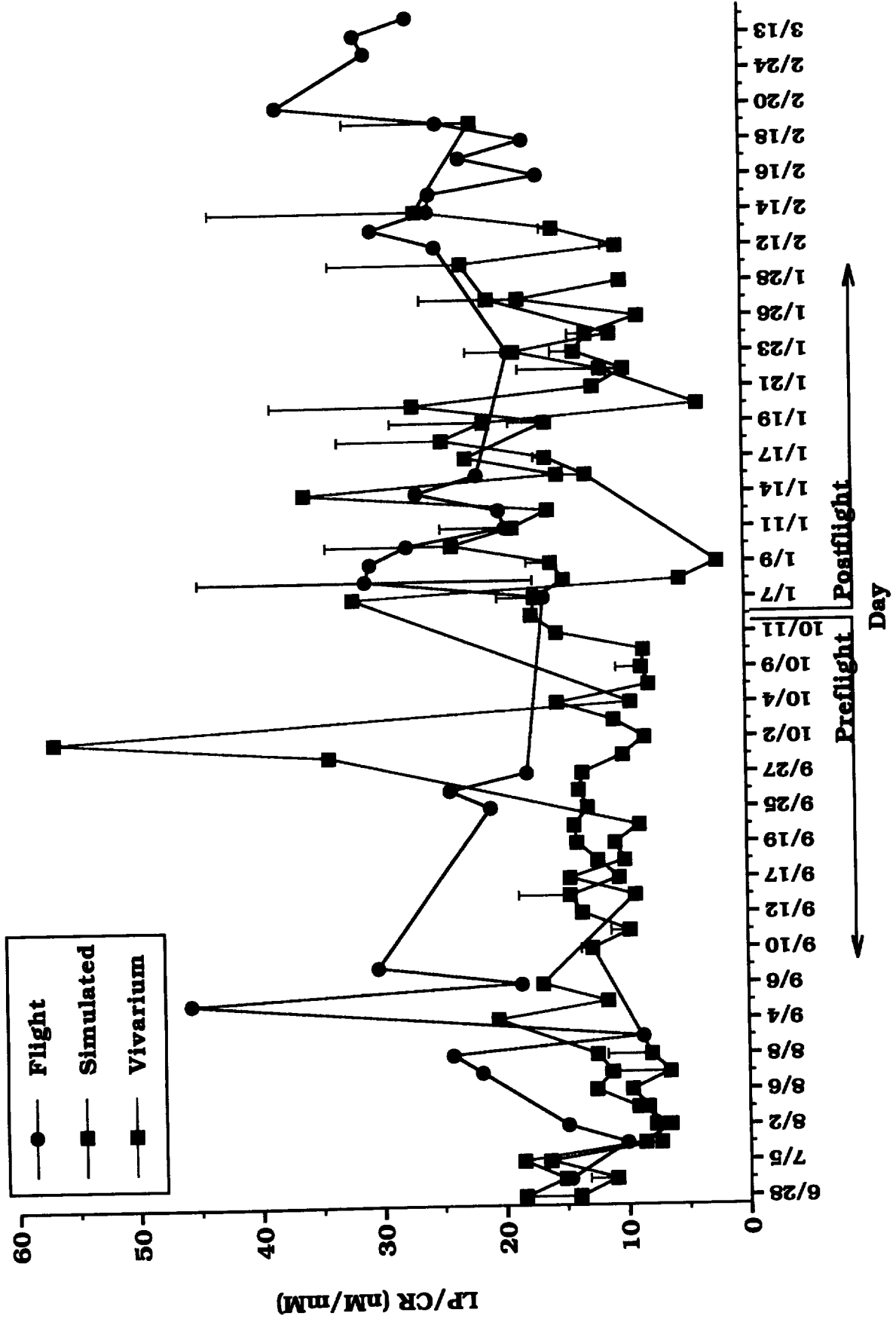
Daily HP/CR values for the 3 Animal Groups



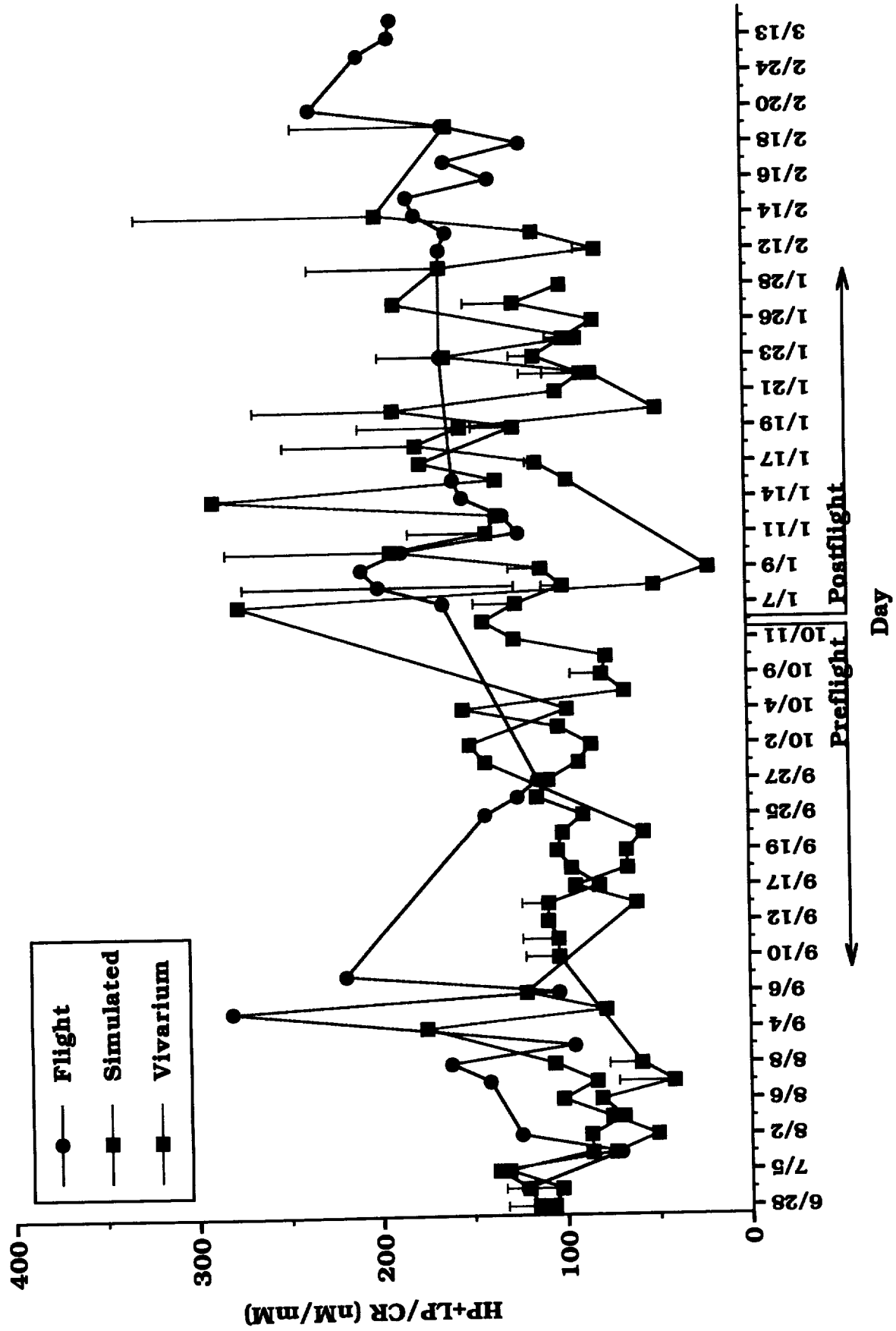
Daily LP values for the 3 Animal Groups



Daily LP/CR values for the 3 Animal Groups



Daily HP+LP/CR values for the 3 Animal Groups



Daily Creatinine values for the 3 Animal Groups

