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# Quantifying body water kinetics and fecal and urinary water output from lactating Holstein dairy cows

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## ABSTRACT

Reliable estimates of fresh manure water output from dairy cows help to improve storage design, enhance efficiency of land application, quantify the water footprint, and predict nutrient transformations during manure storage. The objective of the study was to construct a mechanistic, dynamic, and deterministic mathematical model to quantify urinary and fecal water outputs (kg/d) from individual lactating dairy cows. The model contained 4 body water pools: reticulorumen ($Q_{RR}$), post-reticulorumen ($Q_{PR}$), extracellular ($Q_{EC}$), and intracellular ($Q_{IC}$). Dry matter (DM) intake, dietary forage, DM, crude protein, acid detergent fiber and ash contents, milk yield, and milk fat and protein contents, days in milk, and body weight were input variables to the model. A set of linear equations was constructed to determine drinking, feed, and saliva water inputs to $Q_{RR}$ and fractional water passage from $Q_{RR}$ to $Q_{PR}$. Water transfer via the rumen wall was subjected to changes in $Q_{EC}$ and total water input to $Q_{RR}$. Post-reticulorumen water passage was adjusted for DM intake. Metabolic water production and respiratory cutaneous water losses were estimated with functions of heat production in the model. Water loss in urine was driven by absorbed N left after being removed via milk. Model parameters were estimated simultaneously using observed fecal and urinary water output data from lactating Holstein cows (n = 670). The model was evaluated with data that were not used for model development and optimization (n = 377). The observations in both data sets were related to thermoneutral conditions. The model predicted drinking water intake, fecal, urinary, and total fresh manure water output with root mean square prediction errors as a percentage of average values of 18.1, 15.6, 30.6, and 14.6%, respectively. In all cases, >97% of the prediction error was due to random variability of data. The model can also be used to determine saliva production, heat and metabolic water production, respiratory cutaneous water losses, and size of major body water pools in lactating Holstein cows under thermoneutral conditions.
**Key words:** dairy cow, manure water, mechanistic model, water intake

## INTRODUCTION

In recent years, manure from dairy farms has been identified by regulatory agencies as having a potentially negative effect on air and water quality (Van Horn et al., 1994). Adequate manure storage is needed for convenience and for efficient nutrient recycling and prevention of pollution (Wilkerson et al., 1997). Water in animal excreta and wash water predominantly determine total manure volume, which is a critical factor in designing storage facilities. Moreover, fresh manure volume and composition directly affect chemical reactions releasing nutrients into the environment. For example, volume of urine produced and urea concentration in urine are major determinants of ammonia and nitrous oxide emissions from dairy farms (Bannink et al., 1999; Dijkstra et al., 2013). Manure and soil models, such as the Manure-Denitrification and Decomposition (manure-DNDC) model (Li et al., 2011), mathematically represent postexcretion nutrient dynamics and thereby predict chemical release to the environment. Manure volume and associated nutrient concentrations are vital input variables with these types of models. Moreover, the amount and nutrient concentrations in manure play key roles in land application. For example, with the traditional use of manure as fertilizer, nutrient concentration estimates are important in deciding on storage and transportation requirements and matching crop nutrient needs. Furthermore, water excretion estimates assist in quantifying the water footprint of dairy cows (Mekonnen and Hoekstra, 2012).

Water makes up about 90% of the urine and feces of lactating Holstein cows (Knowlton et al., 2010; Khelil-Arfa et al., 2012). Therefore, accuracy of fecal and

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urinary water estimates considerably affects total fresh manure volume estimates. Several empirical models have been proposed to determine urinary (Holter and Urban, 1992; Bannink et al., 1999; Fox et al., 2004; Nennich et al., 2006; Khelil-Arfa et al., 2012) and fecal (Holter and Urban, 1992; Khelil-Arfa et al., 2012) water excretions from lactating dairy cows. The models of Holter and Urban (1992) and Khelil-Arfa et al. (2012) were constructed using an integrated approach that connected water inputs and excretions. Such an approach allows evaluation of water excretion with respect to whole water balance in dairy cows. However, the fecal and urinary water prediction equations in these models were not optimized simultaneously. Therefore, the corresponding parameter estimates may not appropriately represent the real kinetics involved in body water balance. Moreover, the majority of extant empirical equations were constructed using relatively small data sets (n < 375) and several of them were not evaluated with independent data.

A mechanistic model integrates inputs (e.g., drinking water, water in feed) and outputs (e.g., water in milk, urine, and feces) of a system (e.g., lactating dairy cow) while explaining the transition mechanisms (e.g., gut water passage, absorption). Mathematical representation of transient conditions allows for understanding the system dynamics and for estimating important kinetics and key pools sizes, obtaining absolute measurements of which is quite challenging. For example, knowledge of gut and extracellular water volumes is useful in determining their chemical (e.g., nutrient, metabolite) concentrations and is also important in calculating empty BW and thereby body composition (Andrew et al., 1995). However, predictive power and representativeness of a mechanistic model largely depend on appropriateness of the parameterization, which can be considerably enhanced by solving for all model parameters simultaneously by fitting to a large data set. The objectives of the present study were to (1) develop a mechanistic model representing body water balance and related kinetics for determining fecal, urinary, and total fresh manure water output from lactating Holstein cows, (2) optimize the model for all parameters simultaneously using a relatively large data set, and (3) evaluate the model with data not used for model development and optimization.

## MATERIALS AND METHODS

### Data Sources

A total of 1,047 measured fecal or urinary water outputs (kg/d), and related DMI and drinking water intake (both kg/d), dietary DM percentage and nutrient composition (% of DM), fecal N and total ash excretions (both kg/d), milk yield (kg/d) and composition (%), BW (kg/cow), and DIM were used for analysis. The measurements were made on 315 lactating Holstein cows from 50 energy balance trials conducted at the former USDA Energy Metabolism Unit (**EMU**; Beltsville, MD; Wilkerson et al., 1997). Out of a total of 315 cows, 265 cows provided multiple observations ranging from 2 to 24 observations per cow. Data from 33 experiments (n = 670 observations) were randomly assigned for model development, parameter estimation, and internal model evaluation. Data from the rest of the experiments (n = 377) were allocated for external model evaluation. A summary of these 2 data sets is given in Table 1. Additionally, data on rumen liquid volume (kg) and fractional liquid passage rate from the rumen (/d) measured by rumen emptying, time spent eating ($\boldsymbol{T_{ET}}$) and ruminating ($\boldsymbol{T_{RM}}$) 1 kg of DM (min/kg), and salivary secretion rates (mL/min) measured during eating, ruminating, and resting were extracted from 51 studies in the published literature on lactating Holstein dairy cows (Table 2). Associated DMI, diet nutrient composition, milk production and composition, BW, and DIM were also extracted. See Table 3 for definitions of mathematical notation and parameter abbreviations used in models.

### Model Development

The model was constructed as a deterministic, dynamic, and mechanistic representation of major body water kinetics (Figure 1) in lactating dairy cows. The time unit for fluxes (Figure 1) and the mass unit for the model were days and kilograms, respectively. The model contained 4 body water pools: reticulorumen water ($\boldsymbol{Q_{RR}}$); water in the rest of the gut (i.e., post-reticulorumen compartments; $\boldsymbol{Q_{PR}}$); extracellular water including that in blood and interstitial fluid ($\boldsymbol{Q_{EC}}$); and intracellular water ($\boldsymbol{Q_{IC}}$). Water inputs to $Q_{RR}$ were saliva ($\boldsymbol{F_{Sl,RR}}$), free or drinking water ($\boldsymbol{F_{Dr,RR}}$), and water in feed ($\boldsymbol{F_{Fd,RR}}$). Although water is exchanged between the gut and $Q_{EC}$ via absorption, resorption, and secretions (Remond et al., 1996), for model parsimony, only the net water flows across the reticulorumen wall and rest of the gut wall ($\boldsymbol{F_{RR,EC}}$ and $\boldsymbol{F_{PR,EC}}$, respectively, Figure 1) were included. Some water in $Q_{EC}$ flows back to the rumen via $F_{Sl,RR,}$ and some is used for milk ($\boldsymbol{F_{EC,Ml}}$), urine ($\boldsymbol{F_{EC,Ur}}$) and as respiratory-cutaneous losses ($\boldsymbol{F_{EC,Ev}}$). Water is continuously exchanged between $Q_{EC}$ and $Q_{IC}$ but only a net water transfer from $Q_{IC}$ to $Q_{EC}$ ($\boldsymbol{F_{IC,EC}}$) was included in the model (Figure 1). Metabolic water produced within the cells was added into $Q_{IC}$ ($\boldsymbol{F_{Mw,IC}}$). Although some water can be retained in the body, particularly in early