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Commentary on Applications of Regression in External Dose Reconstruction (ORAUT-RPRT-0087)

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Prepared by

Richard Griffiths

SC&A, Inc.
2200 Wilson Blvd., Suite 300
Arlington, VA 22201-3324

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Abbreviations and Acronyms

DU	depleted uranium
EDA	exploratory data analysis
GLiM	general linear model
K-25	Oak Ridge Gaseous Diffusion Plant
N:P	neutron to photon
NIOSH	National Institute for Occupational Safety and Health
NU	natural uranium
ORAUT	Oak Ridge Associated Universities Team
OLS	ordinary least squares
PGDP	Portsmouth Gaseous Diffusion Plant
QR	quantile regression
ROS	regression on order statistics

1 Summary

The National Institute for Occupational Safety and Health (NIOSH) and Oak Ridge Associated Universities Team (ORAUT) introduced the use of quantile regression (QR) to supply estimates of neutron or beta doses when data are unreliable or doses are unknown in two reports:

- ORAUT (2018): ORAUT-RPRT-0087, revision 00, "Applications of Regression in External Dose Reconstruction"
- NIOSH (2019): "Neutron Dose Assignment for K-25 and Portsmouth Gaseous Diffusion Plants" (White paper)

In ORAUT (2018), the authors present the argument that the flexibility of the QR method will allow for improvement in imputing unknown quantities (e.g., beta doses) from known quantities (e.g., gamma doses) and in meeting project objectives (estimating dose distributions, including percentiles), over the traditional regression-on-order-statistics (ROS) method in many situations.

In NIOSH (2019), the authors employ the QR method to predict neutron doses based on known photon doses as a way to improve on the use of the standard 0.2 neutron-to-photon (N:P) ratio for gaseous diffusion plants. The QR method is used in addition to an analysis of N:P ratios to predict the neutron doses. The authors conclude in the report that "the quantile regression results from the personnel dosimetry measurements at each site would yield the most accurate N:P ratio result" (NIOSH, 2019, p. 16).

SC&A concurs there is merit in postulating that the QR method will better meet project objectives for imputing unknown dose data than the traditional methods in some situations. However, SC&A notes that ORAUT (2018) may have some shortcomings. Any study that proposes to use a regression method to impute dose data should consider that there are important situations in which the ordinary least squares (OLS) or a generalized linear model (GLiM) method will be superior to both the QR and ROS methods. Because of that, SC&A suggests that ORAUT (2018) should better define the manner in which researchers choose between regression methods. It should indicate the types of preliminary analyses that can be conducted to determine the appropriate method for a given evaluation and give some guidance on how the results of those analyses should be used to select the imputation method. Additionally, the guidance should expand on how goodness-of-fit analyses can be used to determine how well the chosen method performs.

Ultimately, SC&A believes that the methods studied in ORAUT (2018)—QR, ROS, and OLS—are among a number of possible methods, any of which may be most appropriate in a given situation. ORAUT (2018) offers some ideas for determining which method might be best in a given situation, but the report would be enhanced if it provided practical guidelines to help researchers determine when the QR method is appropriate and when other methods are more appropriate.

2 Overview of SC&A Commentary

The issue addressed in this commentary—the use of QR to predict or impute unknown doses of one type of radiation from known doses of another type of radiation—first came to SC&A's

attention during an evaluation of a NIOSH white paper specific to the Portsmouth Gaseous Diffusion Plant (PGDP) and the Oak Ridge Gaseous Diffusion Plant (K-25) (NIOSH, 2019). At those sites, paired photon and neutron measurements on personnel dosimetry were not available or reliable until the 1990s. The NIOSH white paper proposes the QR method as a way to estimate neutron doses for the time periods when the neutron measurements were not available or were unreliable.

In "SC&A's Review of NIOSH's White Paper, 'Neutron Dose Assignment for K-25 and Portsmouth Gaseous Diffusion Plants'" (SC&A, 2019), SC&A identified QR as needing further evaluation. SC&A's review led to a series of responses from NIOSH and SC&A:

- NIOSH (2020): "Responses to SC&A's Review of NIOSH's White Paper, 'Neutron Dose Assignment for K-25 and Portsmouth Gaseous Diffusion Plants'" (Response paper)
- SC&A (2020): SCA-TR-2020-SP001, revision 0, "Review of NIOSH February 2020 Response to SC&A (September 2019) on Neutron Dose Assignment for K-25 and Portsmouth Gaseous Diffusion Plants"
- NIOSH (2021): "Responses to SCA-TR-2019-SP002, observation 1, and SCA-TR-2020-SP001," January 20, 2021 (Memorandum)

These technical documents ultimately resulted in QR being identified as a programmatic overarching issue to be evaluated separately.

The present commentary focuses on the QR method as detailed in the ORAUT (2018) technical report but also discusses other regression methods that may be appropriate in different situations. In this document, SC&A addresses the following topics:

- a brief note about QR and how it relates to other regression methods for imputation
- the appropriateness of the QR method to impute unknown doses as discussed in the ORAUT (2018) report
- the appropriateness of the QR method for use in the NIOSH (2019) analysis
- some general thoughts on the QR method, including its general applicability for imputing unknown or unreliable dose measurements from other, known dose measures
- pros and cons of using the QR (or other statistical) method for imputing doses
- some perspective on the categorization of general cases that demonstrate when QR is most appropriate or other regression methods are preferred

3 Quantile Regression versus Traditional Regression

Quantile regression is very similar to ordinary linear regression and other traditional linear regression methods. Its fundamental purpose, to take the ORAUT (2018) application as an example, is to estimate the likelihood of beta dose values for any given gamma dose value. The primary difference is that while OLS regression is usually concerned with estimating the mean beta dose for a given gamma dose, the QR method estimates a percentile of the beta dose distribution given a gamma dose. For instance, the QR method might be used to estimate the *median* beta dose while the OLS regression is used to estimate the *mean* beta dose.

ORAUT (2018) and NIOSH (2019) position the QR method as more flexible than traditional linear regressions since it can be used to estimate any percentile of the beta distribution for a given gamma distribution. In practice, though—and the reports acknowledge this—OLS regression can also be used to estimate any percentile of the beta distribution for a given gamma dose. However, the QR method offers a little more flexibility than a traditional regression method since the estimated percentiles of a traditional regression all fall on lines (mapped over all gamma values) with the same slope. The QR method allows for different slopes for each estimated percentile.

The calculations used to estimate the parameters of a QR (e.g., intercept and slope for a simple linear model) are different than those used in the OLS regression. The QR calculations require minimizing sums of absolute differences between the QR line and the observed beta values, whereas the OLS calculations require minimizing the sums of the squared differences between the OLS line and the observed beta values. It's a subtle difference but one that has an effect on the interpretations of the slope and intercept estimates and makes a difference in the complexity of the underlying calculations performed by the appropriate software.

On a practical and fundamental level, though, QR and the traditional regression methods are not all that different. SC&A acknowledges that the QR method has many clear benefits (e.g., it provides a nontraditional way to work with the distribution of beta doses for given gamma doses and it can add flexibility for the estimation of distribution percentiles), but it is not necessarily a "better" solution than traditional regression methods in all situations. In SC&A's view, it is mainly a different way of addressing estimation problems that may or may not better accomplish the programmatic goal (in this case, ultimately developing dose reconstruction methods to account for missing or unreliable data).

4 Appropriateness of Quantile Regression in Dose Reconstruction

In ORAUT (2018), the authors state their case for the QR method to be used to estimate or impute unknown radiation doses of one type based on known doses of another type. They postulate that the flexibility of the QR method will provide an improvement in imputing unknown quantities (e.g., beta doses) from known quantities (e.g., gamma doses) and in meeting project objectives (estimating dose distributions, including percentiles) over the ROS method in many situations. They perform a goodness-of-fit analysis to highlight the potential improvements in the scenario discussed in the report.

However, the methods of comparison—in particular, the goodness-of-fit analyses of ORAUT (2018)—should be expanded and formalized to make an accurate determination of the situations for which QR is most suited. Additionally, there are likely important situations in which the OLS method, or a GLiM, will be superior to both the QR and ROS methods. Some preliminary analysis of the data would be beneficial in helping to determine which method is applicable in a given situation before any regression method is applied.

Observation 1. ORAUT-RPRT-0087 would benefit from expanded guidance on how to use preliminary statistical analyses to determine which regression methods are best for different datasets representing different practical scenarios.

In this section, SC&A reviews some of the candidate regression methods that could be used to impute unknown radiation doses and further discusses the topics of preliminary and goodness-of-fit analyses that can help determine which methods are appropriate in which situations.

4.1 The candidate analytical methods

In section 8.0 of ORAUT-RPRT-0087, the authors state the following regarding the applicability of the candidate analysis methods:

> The choice of which method to use depends on the specifics of the dataset and the desired results for the particular application. For this reason, a statistician and subject matter expert should jointly determine the best method based on those specifics. [ORAUT, 2018, p. 28]

The authors thus make clear they are not suggesting the QR method is best in all cases, only that it should be considered as an additional tool. The statement suggests there may be cases where another regression method might be more appropriate; however, ORAUT (2018) does not speculate on how to determine that. It only introduces OLS and QR as alternatives to ROS regression without discussing when OLS or QR or another regression method may be most appropriate.

All of the methods considered in ORAUT (2018) are viable ways to impute for unknown quantities (e.g., beta doses) based on known quantities (e.g., gamma doses). The QR and OLS regression methods differ formulaically from the ROS regression primarily in the manner in which the known data pairs are used. In particular, the ROS method regresses the ratio of known beta-to-gamma dose on quantiles of a hypothetical statistical distribution. Neither the OLS nor QR methods combine the beta and gamma doses into a ratio. Instead, both methods regress beta doses on gamma doses.

The OLS and ROS methods are similar in that they rely on the assumption that the data follow a standard statistical distribution. Going beyond the assumption of normally distributed data, one can hypothesize that if the underlying distribution of the data (e.g., beta dose) is from the exponential family of distributions (to which the normal distribution belongs), a GLiM of similar form to the OLS model studied in ORAUT (2018) can be applied. Similarly, the ROS method could be applied with quantiles of the exponential-family distribution on the right side of the model. So, while the OLS, GLiM, and ROS methods require an assumption about the underlying data distribution, non-normal data can be handled by these regression methods.

In contrast to OLS, GLiM, and ROS, the QR method is agnostic to the distributional form of the underlying data. This is an important distinction in that it provides a clue as to which method might be best in a given situation. The QR method, though, does generally require larger sample sizes than the other methods.

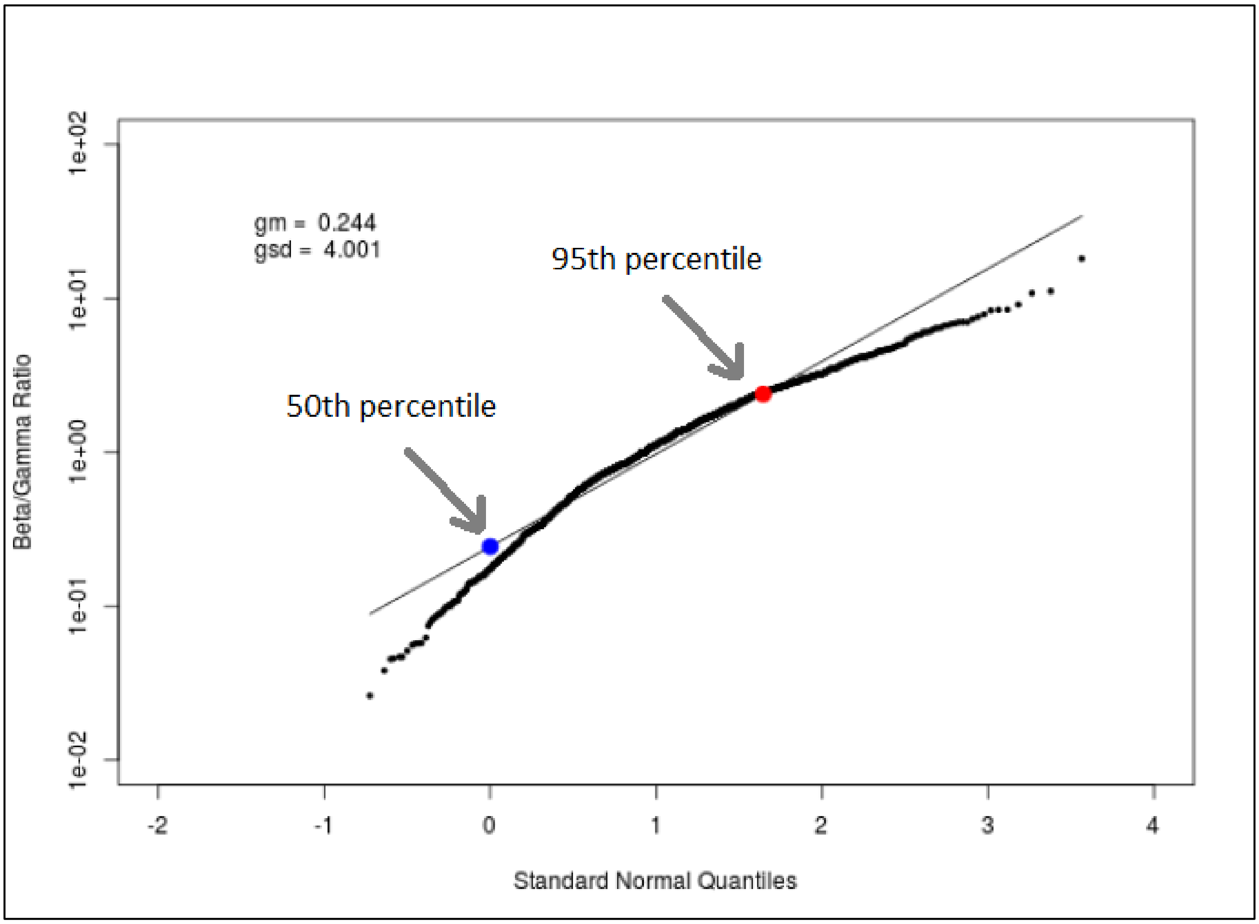
Additionally, if the variability of the underlying data differs by level of the independent variable (heteroscedasticity), an adjustment needs to be made to the data for the OLS, GLiM, or ROS methods to work effectively. The QR method is not constrained by this condition.

Consideration of these issues helps set the stage for figuring out where the QR method is better than the ROS method and where OLS/GLiM methods might be deemed best.

4.2 Which method is best and in which situations?

There are both pre-analysis and post-analysis methods the statistician might use to establish which method is the most appropriate imputation method in any given situation. ORAUT (2018) does present one pre-analysis method: a lognormal Q-Q plot of beta/gamma ratios in figure 4-1 (reproduced here as figure 1). This plot may be considered one way of helping a researcher determine which regression methods are appropriate prior to analysis. In this figure, the logarithmically scaled beta/gamma ratios of the analysis data set are plotted against quantiles of the standard normal distribution. As the report notes, the figure indicates that the normal distribution does not fit the beta/gamma ratios well. It is not surprising then that the ROS method doesn't work well to predict beta doses for this data. If used as a preliminary analysis, this ratio-to-normal quantile figure would have suggested that the ROS method would not be the best method in this case. Perhaps, the ROS method might work better on other datasets, but ORAUT (2018) is spare in suggesting guidelines for how to establish where the ROS method might actually prove superior to the QR method.

Figure 1. Lognormal Q-Q plot of beta/gamma ratios where the line is the fit from the lognormal ROS (screenshot of figure 4-1 of ORAUT (2018) with 50th and 95th percentiles identified)



Beyond the Q-Q plot, however, there are other pre-analysis methods that might be considered. ORAUT (2018) would benefit from a deeper discussion of these methods. Some pre-analysis methods worth mentioning include:

- More detailed graphical analyses of the data distributions, such as histograms and box plots. These visuals can be powerful tools for the researcher to use to understand the types of underlying distributional assumptions that are appropriate.

- Statistical testing for the form of the underlying dose distribution. These tests complement the visuals with a formal quantification of the distributional assumptions that might be appropriate for modeling.

An important preliminary analysis to do when considering which of a number of regression methods should be used would be to determine if the underlying distribution has the form of an exponential-family distribution. The normal distribution is one member of the exponential family, and an OLS regression might be more appropriate in the case of normal dose distributions than the QR method. Generally, exponential-family distributions are associated with standard regression techniques.

As an example of why this is important to mention with regard to ORAUT (2018) and for determining which method is best in a given situation: If the underlying beta dose data are normally distributed or lognormally distributed, the most appropriate method for imputing beta doses is likely the OLS method, not the QR method or ROS method. This possibility isn't considered in ORAUT (2018) since the goodness-of-fit of the OLS method is not studied in detail.

Beyond the normal and lognormal distributions, there are a number of different and common distributions in the exponential family that can be modeled with a GLiM, which may be a more appropriate method than the QR method in such situations. So, it is important to think about the exploratory data analysis (EDA) methods and statistical tests that can be used to help determine appropriate methods prior to settling on a regression method. ORAUT (2018) would benefit from more information on these types of preliminary analyses.

Observation 2: ORAUT-RPRT-0087 would benefit from a more extensive discussion of different pre-analysis methods (e.g., Q-Q plots, histograms, box plots, and other statistical testing methods) that should be utilized prior to selecting a regression method to inform the analyst of the underlying distribution of the data.

ORAUT (2018) takes some care to compare the results of the QR model fit to the ROS model fit. This is an important, post-analysis step to determine which method is best for the data discussed in that report. Goodness-of-fit comparisons, as well as other methods such as cross-validation and formal statistical testing of the prediction results, can be used effectively by the statistician to help establish the situations in which each of the regression methods might be best. ORAUT (2018) would benefit from expanded coverage of post-analysis evaluations beyond the QR-ROS goodness-of-fit comparison.

Observation 3: The methods of comparison discussed in ORAUT-RPRT-0087, in particular the goodness-of-fit analyses, should be expanded and formalized for accurate determination of QR method suitability. In addition to goodness-of-fit analysis, additional post-analysis methods such as cross-validation and statistical testing of the predicted results are warranted to inform the analyst of the appropriateness of their chosen regression approach.

4.3 Quantile regression versus regression-on-order-statistics

The overarching issue is the applicability of the QR method to situations in which a researcher is imputing unknown quantities based on known quantities. As noted in section 4.1, there are a number of regression methods besides QR that might be used on any given dataset. In this section, SC&A will focus on the QR-ROS comparison since it is the one ORAUT (2018) addresses in most detail.

As explained in ORAUT (2018), the ROS method has been used extensively in dose reconstruction and is considered as a means for imputing beta dose from gamma dose. In section 4.0 of ORAUT (2018), the authors noted the poorness of fit of the ROS model to the study data. However, this does not establish that a QR is better. The poorness of fit for the ROS method applies only to the dataset under analysis in the report. Going back to the discussion of figure 4-1 (refer to figure 1 in section 4.2 of this report), it was clear there that the assumption of normality underpinning the ROS model is violated. This highlights the importance of preliminary analyses. While other preliminary analysis methods could have been used to complement the figure 4-1 graph and analysis, that figure itself lent evidence to the idea that the ROS model was not appropriate for the report's data.

Beyond that, ORAUT (2018) does provide some reasons for why the ROS method could be improved on. One is the reliance of the ROS method on use of a beta/gamma dose ratio as the dependent variable, which is restrictive. Additionally, the implication of the goodness-of-fit analysis is that the ROS model is not well specified. So, there is a question as to whether a better specification of the ROS model would lead to a better fit. ORAUT (2018) does not explore this possibility.

In section 6.0 of ORAUT (2018), the authors review the QR method. In section 7.0, they look at the goodness of fit of the quantile regression. This can be compared to the goodness of fit of the ROS model in section 4.0 and, as ORAUT (2018) notes, the QR fit looks better than the ROS model fit. However, the improvement in fit is not quantified, nor is it tested for statistical significance.

Another way of quantifying the improvement—and possibly a more intuitive method of comparison—brought by the QR would be a cross-validation study. A cross-validation study would help users understand how well the different models predict beta doses outside the data used to fit the models. A cross-validation study should be straightforward to conduct and could also be applied to the ROS and OLS/GLiM models, so all models could be compared formally. As it stands, there is no formal, statistical comparison of the fits of the ROS and QR models. ORAUT (2018) could benefit from a further consideration of post-analysis methods that examine the fits and predictions in a broader range of data. (Refer to observation 3.)

4.4 OLS/GLiM comparison

SC&A notes there are important situations in which an OLS or GLiM is going to be the best approach. These considerations are not discussed in ORAUT (2018). As an example of an important situation, if the distribution of the beta doses were lognormal, the GLiM method (or, OLS method on log-transformed data) would be more efficient than the QR method in the sense that estimates from the GLiM would be more precise. The QR method requires large sample sizes to fit its numerous regression lines for the various distribution percentiles; the OLS and GLiM do not require sample sizes quite as large. Because of this, QR loses its primary advantage over GLiM (or OLS) of being distribution-agnostic when the distribution is well assured.

Observation 4: While the QR method represents an appropriate and flexible method for regression analysis (in particular when the underlying distribution is unknown), the method may be less appropriate than other regression methods when the sample size is relatively small and/or the underlying distribution is normal/lognormal.

In ORAUT (2018), the OLS regression method is introduced as an alternative to the traditional ROS approach; however, it is not explored as thoroughly as the QR method. ORAUT (2018) evaluates the goodness-of-fit of the ROS and QR models for the particular data set they analyzed in the report. However, ORAUT (2018) did not perform a similar analysis for the OLS method. ORAUT (2018) would benefit from a discussion of how the OLS and QR model fits might be compared.

ORAUT (2018), section 5.0, reviews OLS regression and demonstrates how it works for estimating quantiles of beta doses; however, the report does not address whether OLS produces better predictions of beta doses than does the ROS model. As noted previously, the report does not study the goodness-of-fit of the OLS model. Section 7.0, page 23, notes that a goodness-of-fit procedure could be applied to the OLS regression results, but the calculations are not performed. This analysis should be done to help readers understand how well the OLS regression might meet the evaluation objectives in a situation similar to that of the report. There will be situations in which an OLS or GLiM regression is more appropriate for imputing doses than QR or ROS and more detail on analyses that can be used to make a determination for a given situation would benefit ORAUT (2018). (Refer to observations 2 and 8.)

In short, it would aid an understanding of where the OLS method is appropriate if a full OLS-ROS-QR comparison had been performed in this report. Additionally, a comparison of OLS to QR and ROS for a data set in which the underlying distribution is normal or lognormal would be useful.

4.5 Miscellaneous comments

SC&A noted several additional issues in the analysis and evaluation in ORAUT (2018). However, these additional comments do not have a significant bearing on SC&A's opinion about the appropriateness of QR for imputing unknown doses.

Observation 5: SC&A provides the following six editorial comments for completeness of the review and consideration if/when ORAUT-RPRT-0087 is revised:

- **Comment 1:** SC&A understands the purpose of the example of the bad fit given in section 7.1; however, simply specifying a model with a bad fit and comparing it to the model in equation (6-1), doesn't mean (6-1) is the right model. It would have been more fruitful to compare the fit of equation (6-1) to that of the ROS model and the OLS model.

- **Comment 2:** ORAUT (2018) does not contain a discussion about the statistical error involved in imputing unknown doses and its effect on downstream uses of the imputations. The topic of multiple imputation has come up in a few different reports (e.g., ORAUT, 2021). Multiple imputation could be used to (1) understand the quality of OLS or QR or ROS regression imputations, (2) provide a measure of precision of the imputations and thus a measure of their quality, and (3) quantify the amount of uncertainty those imputations induce in probability of causation calculations or other downstream modeling processes. Even if multiple imputation is not used, the precision of the imputations should be quantified.

- **Comment 3:** There should be a subscript on the regression coefficients in equation (6-1) to make clear the need for a separate regression with different slope and intercept estimates for each quantile x modeled:

$$Q_x (H_\beta) = \beta_{0x} + \beta_{1x} H\gamma$$

- **Comment 4:** In equation (6-1), the Greek letter β is used to refer to both a type of dose and the regression parameters. That could be confusing to some readers.

- **Comment 5:** In section 2.0 of ORAUT (2018), there is a discussion of how the censored data were treated for analysis. The rationale for imputing for only a portion of the data is unclear to SC&A. Only data corresponding to types 1 and 3, as defined in section 2.0, are used in the analysis and thus imputed for. The reason given is that OLS and QR require uncensored observations. This is not entirely true: Both types of regressions can be adapted to handle censored observations. Instead, it appears the reason for using only types 1 and 3 data is that for the other two types of data the beta-to-gamma ratio is undefined when the gamma dose is censored. SC&A believes that ORAUT (2018) could clarify this rationale.

- **Comment 6:** Additional clarification in section 3.0 of ORAUT (2018) regarding how the censored gamma doses were treated would be helpful. It appears to SC&A that the censored beta doses were imputed for but not the censored gamma doses. If that is true, and the censored gamma doses were left at their censored values, that would bias results of any modeling. SC&A believes clarification is warranted to understand how these data were utilized.

4.6 Summary points

In summary, the QR method is appropriate for the analysis in ORAUT (2018) because it is a statistically sound method for estimating unknown doses of one type of radiation from known doses of another type. However, it may not be the best method for every situation. To determine if it is the best method for the ORAUT (2018) scenario, more work is warranted to assess the ability of the QR, OLS, GLiM, and the ROS methods to meet the evaluative and analytical objectives. Particularly since ORAUT (2018) appears to be a technical report designed to serve as a reference for future study design, those preliminary analysis methods should be outlined so the researchers of future studies know how to determine the most appropriate regression method for their unique analysis. Additionally, more information about the types of goodness-of-fit tests that can be used to assess the ability of any of the methods for accurately imputing unknown doses should be given.

5 Appropriateness of Quantile Regression for NIOSH (2019) Analysis

The paper that originally brought the QR method to SC&A's attention was NIOSH (2019), though the method had previously been discussed in ORAUT (2018). Since NIOSH (2019) implements the guidance in ORAUT (2018), SC&A examines the appropriateness of QR for the case of imputing neutron doses from photon doses in NIOSH (2019) from the perspective laid out in the previous section.

5.1 General commentary

SC&A identified and analyzed the datasets associated with the NIOSH (2019) evaluation. Ultimately, SC&A was unable to duplicate all counts of analyzed doses from each of the sites reviewed in that paper. The source of the discrepancy is unknown at this time; however, SC&A believes the focus of its review should be on the general use of the QR method in the report and its appropriateness for the data presented in NIOSH (2019).

NIOSH (2019) discusses the basis for the recommended N:P ratio of 0.2 and puts forth the general belief that the methods used to develop the recommended ratio and the resulting recommended ratio have limited justification. NIOSH (2019) notes that the "data resulting from the quantile regression analysis of personnel dosimetry provide the best estimate for an overall N:P ratio for unmonitored workers" (NIOSH, 2019, p. 16).

Ultimately, SC&A is in favor of the QR method as it compares to the method used to develop the recommended 0.2 ratio as outlined in NIOSH (2019); however, SC&A feels that the final evaluation of the QR method may be lacking. There is no data-based comparison in the paper to suggest that the QR method is less statistically biased and more precise than the method used to derive the original 0.2 recommendation. Being inclined toward the QR method, SC&A believes it is likely more precise and less biased, but the evaluation should have laid out the comparison more quantitatively. Looking at this from the perspective of someone for whom the QR method is somewhat novel, more justification of the QR method in this instance is likely important.

5.2 Method versus model specification

It is one thing to consider the QR method applicable to the NIOSH (2019) data; it is another to think about the type of QR model that is most appropriate for the analysis. In both NIOSH (2019) and ORAUT (2018), the same basic QR model is used as a method for analyzing the relationship of beta-gamma or neutron-photon dose pairings. In both, one type of dose is modeled as a linear function of another type in slope-intercept form. While this simple form is powerful and the most straightforward of QR models to understand, it can oversimplify the actual relationships between beta-gamma or neutron-photon dose pairings. In NIOSH (2019), there is evidence to suggest that N:P ratios vary by other factors:

- Type of uranium (depleted (DU), natural (NU), low-enriched, or high-enriched)
- Facility
- Location of storage cylinders
- Atmospheric conditions
- Distance

Additionally, NIOSH (2019) cites the following quantitative N:P ratio variations by facility and other factors:

- ratios ranging from 0.14 to 0.42 with an average of 0.20 at the Paducah facility for outside uranium hexafluoride cylinders containing DU and NU (NIOSH, 2019, p. 3).
- N:P ratio of approximately 0.5 for empty cylinders and 1.2 for full cylinders at PGDP (p. 4)

- average N:P ratio of 0.147 (±0.09) with a range of 0.01 to 0.398 for outdoor cylinders at PGDP (p. 4)
- 0.369 for an average over 161 records from PGDP dosimetry data (p. 6)
- 0.166 for cylinder yard measurements and 0.274 on the outside boundary of a cylinder yard at the K-25 facility (p. 7)
- a K-25 modeling study that examined the effect of distance and air relative humidity on N:P ratio, with values of 0.1, 0.22, and 0.88 at 1-meter distance under varying humidities and then 0.2, 0.4, and 1.5 at farther distances under the same humidity measurements (p. 7)
- 0.099, 0.085, and 0.122 at contact, 1 foot, and 1-meter distances for an area monitoring survey at K-25 (p. 7)
- 0.605 ± 0.408 from general area measurements at K-25
- 0.420 based on 369 records in the East Tennessee Technology Park database (p. 9)

This evidence is suggestive of the need to account for other factors in the model. To produce an accurate estimate of the N:P ratio for any given individual or an accurate estimate of the distribution of N:P ratios for a group of individuals, the model should acknowledge the differences in exposure among individuals who worked under different conditions. Accounting for these factors could be done by including them as covariates in the QR or other regression model. It is unlikely that including covariates in the model would add greatly to the complexity of interpretation or the difficulty of setting up the model in the analysis software.

Observation 6: The usefulness of covariate information should be considered when determining the form of the QR model most appropriate for a given analysis.

5.3 Preliminary analysis

In accordance with earlier SC&A commentary in this report concerning ORAUT (2018) (refer to observation 2), SC&A believes NIOSH (2019) should have used some exploratory data analysis to determine whether the QR method was the most appropriate regression method to use in this situation. In situations where the underlying data can be assumed to be normal or lognormal, it is possible that an OLS regression will be more precise than a QR and thus more appropriate. NIOSH (2019) does not attempt to conduct this kind of preliminary analysis, so one cannot judge whether the QR method was the best method to use.

Also as noted in section 5.2, there is no analysis to discover factors that might affect the neutron-photon relationship. A preliminary analysis that looks at whether the N:P ratio might differ by factors like job type or varying atmospheric conditions could provide information about whether covariate factors should be include in a regression model to make the imputations more precise.

5.4 Post-analysis evaluation

There is limited statistical evidence provided in NIOSH (2019) to back up the statement that "the quantile regression results from the personnel dosimetry measurements at each site would yield the most accurate N:P ratio result" (NIOSH, 2019, p. 16). As noted in SC&A's comments on

ORAUT (2018), measuring the precision of the resulting N:P ratio estimates and statistically testing the fit of the QR model for the N:P ratio estimates would help the reader to understand how appropriate the QR method was for this analysis (refer to observation 3). It would also provide information for understanding the effect of N:P ratio imputation on downstream processes.

Observation 7: To provide readers with quantified evidence of QR being an accurate method of analysis, NIOSH (2019, SRDB 176609) should measure the precision of the N:P ratio estimates and provide results of statistical testing of the QR fit for the N:P ratio estimates.

6 General Thoughts on the QR, OLS, and Other Regression Methods for Imputation

6.1 Improvements offered by the QR and OLS methods

The QR method is distribution agnostic, whereas the OLS, ROS, and GLiM methods make some assumptions about the underlying statistical distribution of the analysis data. It stands to reason that for datasets for which one is interested in imputing dose amounts that follow an unknown (or nontraditional) statistical distribution, the QR method may offer a benefit over methods such as ROS, OLS, and GLiM that assume a functional form for the distribution. In such cases, one would expect QR to provide less biased estimates of dose percentiles and distributions.

The QR method allows percentiles of a distribution to be modeled by different regression lines. That is, each quantile regression line may have a different intercept and slope. If this is an important consideration for a particular dataset or project, it can be an advantage over the other models discussed in this commentary. On the downside, the QR method requires larger sample sizes to fit these separate quantile regression line parameters and can thus be less precise than other methods.

Relative to the ROS method, the QR and OLS methods are less restrictive in their functional formulations. In the ROS model discussed in ORAUT (2018), the ratio of the two doses is given as a function of a standard normal quantile. The QR and OLS methods can also model the ratios of the two doses as the function of a standard normal quantile; however, both allow for other formulations, such as a beta dose as a function of a gamma dose.

All of the methods discussed previously—QR, OLS, and GLiM—can accept covariate information to improve imputations. For instance, if doses vary by worker type, that information can be incorporated into all of these types of models, either via an explicit independent variable in the mathematical formulation or through stratification/subsetting.[1]

The pros and cons listed in section 6.4 of this report include these observations, as well as offering some additional discussion of the relative benefits of each imputation method.

[1] The ROS model can also be adapted to stratification by worker type.

6.2 General applicability of the QR method for imputation

The QR method would seem to be generally applicable where the analyst has known and accurate measurements from one type of radiation and is seeking to impute measurements for another, related type of radiation that has not been measured or has been measured inaccurately for some reason. The analyst must be able to specify the relationship between the two types of radiation within the constraints of the linear form of the QR model. That, however, is not necessarily as restrictive as it might seem since the variables that represent each type of radiation can be transformed as need be (e.g., log transformations) to adapt the QR method. It also helps if the analyst is capable of (1) performing some preliminary analyses to correctly specify the form of the relationship between the radiation types and (2) understanding the role covariate information might play in the formulation of the QR model.

The QR method will not work in all situations, though. Some situations where the method would not be viable:

- no covariate data, e.g., no known doses from other radiation types
- datasets with small sample sizes (Other methods that do not require the estimation of a large number of parameters may give more precise imputations.)
- instances in which the analyst is not comfortable with the extra complexity of making inferences from the QR analysis
- the resources for the analysis are not commensurate with the extra complexity of coding and interpreting the QR method
- the project goals do not require estimation of quantiles

6.3 Applicability of other statistical methods to impute unknown or unreliable dose measurements from other, known dose measures

Numerous methods other than QR can be used to impute unknown, missing, or unreliable dose measurements from other, known dose measurements. ORAUT (2018) notes that other methods, such as simple ratios (e.g., half of the level of detection) and other regression methods (e.g., ROS), have been used in the past. These are still viable methods and may be advantageous in some situations. ORAUT (2018) further mentions OLS as another regression method that can perform this same function. Finally, as SC&A noted previously, GLiM is yet another possibility. These are a few statistical methods that could feasibly be used to impute doses, but there are many others that could be used to perform imputations in the presence of covariate (known doses) information. SC&A's primary position here is that the appropriate imputation method to use depends on the situation. Some of the mentioned methods will be good in some situations and not so good in other situations.

6.4 Pros and cons of the QR method for imputing doses

This section lists some of the benefits (pros) and limitations (cons) of the QR method for imputing dose.

Pros:

- The QR method has the advantage over the other methods in that it can be used to estimate a quantile without overlaying an assumed statistical distribution. So, if the underlying population distribution of doses is not known, the QR method can be used without preliminary analysis to diagnosis the form of the underlying distribution.
- QR offers flexibility in modeling percentiles. The ROS, OLS, and GLiM methods all assume that the linear relationship between the dose to be predicted and the dose variables to be used as predictors has the same slope for each percentile. The QR method allows the slopes to vary depending on the percentile.
- If the variability of the underlying data varies by level of the independent variable (heteroscedasticity), an adjustment needs to be made to the data for the OLS, GLiM, or ROS methods to work effectively. The QR method is not constrained by this condition.
- Any statistical method, such as QR, can make use of information pertinent to understanding relationships between dose types. Methods of imputation based on constant ratios (e.g., 0.2 N:P ratios (NIOSH, 2019, p. 3)) do not make use of all information available.

Cons:

- The QR method is more complex than imputation methods based on ratios (e.g., 0.2 N:P ratio), ROS, or even the OLS methods.
    - Not easily implemented in commonly available software, like Microsoft Excel. Would require development of code in R, SAS, or another statistical software.
    - Requires advanced statistical skills to interpret results.
    - Would require more care in set-up, analysis, and interpretation of results to avert mistakes.
- Sample sizes need to be larger for QR than for ROS, OLS, or GLiM owing to the fact that each quantile requires a different intercept and slope estimate. This is not an issue if the user is estimating only one quantile but becomes an issue for other uses, such as trying to fit a distribution based off a QR.
    - For instance, the last paragraph of section 6.0 of ORAUT (2018) discusses fitting QRs for 21 quantiles. The authors correctly note that each of these estimated quantiles is the result of separate QR fits—one for each quantile—and that this makes the QR method more flexible for estimating a distribution than the other methods. The cost of this, though, is that a larger sample size is needed to estimate 42 slopes and intercept parameters involved in estimating the 21 quantile regression lines. The OLS regression only requires estimation of 2 parameters: one slope and one intercept. This means the parameter estimates of the QR

method are less precise than those of the OLS method, a point not discussed in ORAUT (2018).

- ORAUT (2018, p. 8) notes that the ROS method deals well with censored observations, but imputation needs to be used for the QR method in order for it to make use of the full data set.

- The QR method can produce nonsensical results such as the 95th percentile of a beta dose being less than the 90th percentile for a given gamma dose. It is probably more prone to doing this when sample sizes are relatively small.

- Often, in external dosimetry applications, the data distribution can be assumed to be normal or lognormal. In these applications, OLS and GLiM have an advantage over the distribution-agnostic QR method.

7 Categorization of Situations in which Each of the Statistical Methods May Be Appropriate

SC&A believes that ORAUT (2018) would be enhanced if NIOSH provided a set of practical guidelines for the use of QR. SC&A suggests these guidelines be constructed to include a general categorization of the situations in which QR is appropriate and when QR is not appropriate. Table 1 of this SC&A report gives a few examples. This table is not exhaustive of all situations but should give some idea of a categorization that would be useful to researchers when they need to determine whether to use the QR method for an analysis.

Table 1. Regression analysis methods to consider in some situations

Situation	Which methods to consider for analysis	Comments
If the statistical distribution of the underlying data is unknown or is not of a standard form	Consider QR	OLS and GLiM assumptions are violated if the data are from something other than an exponential-family distribution.
If the data can be assumed to be from a lognormal or other exponential-family statistical distribution	Consider an OLS or GLiM	Formal statistical tests should be used to determine if the underlying data come from an exponential family.
If the sample size is small	Consider a method other than QR	QR requires a relatively large sample size to support estimation of parameters at several quantiles.

Observation 8: NIOSH should consider constructing clear and practical guidelines for the intended analyst that outline situations when quantile regression is and is not appropriate.

8 Conclusion

The ROS method is not the only or best regression method to impute beta doses from gamma doses (or one type of unknown dose from another known dose) in every situation. Neither is the QR method. SC&A believes there are a number of steps that could be taken to solidify the advice given in ORAUT (2018), as identified in the previously discussed eight observations, and help project statisticians and analysts determine which analysis method is appropriate in any given situation with which they are confronted:

- To give the reader an idea of which methods are best in which situations, advice should be given on how formal statistical tests of the quality of fit of the ROS, QR, OLS, and GLiM methods can be used to determine which method to use in various practical scenarios that are known to occur. (Refer to observation 1.)

- Practical guidelines on how to choose the most appropriate method for the situation should be offered. ORAUT (2018) concludes that "a statistician and subject matter expert should jointly determine the best method" (ORAUT, 2018, p. 28), so a deeper dive into guidelines in this or a future report might help the statistician and subject matter expert to decide. Project objectives should be considered, such as whether mean or median point estimates are needed and whether estimated distributions are needed. (Refer to observation 8.)

- NIOSH should consider expanding the discussion of how EDA can be used to establish which distributional scenario is presented in each situation. NIOSH should show how to test model assumptions during the EDA. Additionally, NIOSH should establish a resource that offers guidelines for choosing the best methodology for given situations. (Refer to observations 2 and 8.)

- Preliminary analysis, perhaps part of the EDA, could also help suggest other factors to include in the model that would improve dose imputation. For instance, knowing that "the magnitude of the neutron flux varies based on total activity of the uranium (a function of enrichment) and the chemical compound (combining of uranium with fluorine or oxygen)" (NIOSH, 2019, p. 2) is suggestive of the need for enrichment level and chemical compound to be included in a model for neutron dose. (Refer to observation 6.)

- The question of the statistical error and uncertainty of the imputations should also be considered. Multiple imputation has been mentioned in a number of reports and is used in ORAUT (2018, p. 8), but to understand the quality of OLS or QR or ROS regression imputations, a measure of precision should be calculated. Multiple imputation is one method for estimating the statistical error of the imputations. To be certain, there are other methods that could be considered, such as resampling methods (Monte Carlo simulations are discussed in ORAUT (2018)), that could help with understanding uncertainty. (Refer to observation 7.)

- If QR-based imputations are to be used to estimate a distribution (for a co-exposure development, for example), consideration should be given to whether the dataset is large enough to support the QR method, which requires relatively large sample sizes for estimating parameters at many quantiles. (Refer to observation 4.)

- Section 8.0 of ORAUT (2018) notes that the QR method may not be the best method in all cases:

> The choice of which method to use depends on the specifics of the dataset and the desired results for the particular application. For this reason, a statistician and subject matter expert should jointly determine the best method based on those specifics. [ORAUT, 2018, p. 28]

It is thus clear that NIOSH is not suggesting the QR method is best in all cases, only that it should be considered as an additional tool; however, ORAUT (2018) does not speculate on how to determine that. It only introduces OLS and QR as alternative tools. ORAUT (2018) should offer more advice on how to determine which method is best in which situation. (Refer to observations 1, 2, and 3.)

9 References

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