Traditional Biomolecular Structure Determination by NMR Spectroscopy Allows for Major Errors

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One of the major goals of structural genomics projects is to determine the three-dimensional structure of representative members of as many different fold families as possible. Comparative modeling is expected to fill the remaining gaps by providing structural models of homologs of the experimentally determined proteins. However, for such an approach to be successful it is essential that the quality of the experimentally determined structures is adequate. In an attempt to build a homology model for the protein dynein light chain 2A (DLC2A) we found two potential templates, both experimentally determined nuclear magnetic resonance (NMR) structures originating from structural genomics efforts. Despite their high sequence identity (96%), the folds of the two structures are markedly different. This urged us to perform in-depth analyses of both structure ensembles and the deposited experimental data, the results of which clearly identify one of the two models as largely incorrect. Next, we analyzed the quality of a large set of recent NMR-derived structure ensembles originating from both structural genomics projects and individual structure determination groups. Unfortunately, a visual inspection of structures exhibiting lower quality scores than DLC2A reveals that the seriously flawed DLC2A structure is not an isolated incident. Overall, our results illustrate that the quality of NMR structures cannot be reliably evaluated using only traditional experimental input data and overall quality indicators as a reference and clearly demonstrate the urgent need for a tight integration of more sophisticated structure validation tools in NMR structure determination projects. In contrast to common methodologies where structures are typically evaluated as a whole, such tools should preferentially operate on a per-residue basis.

Introduction

Experimentally determined three-dimensional structures of biomolecules form the foundation of structural bioinformatics, and any structural analysis would be impossible without them. Two main techniques are available for biomolecular structure determination: x-ray crystallography and nuclear magnetic resonance (NMR) spectroscopy. It is important to realize that all resulting structure models are derived from their underlying experimental data. Unfortunately, any experiment and thus any structure model will have errors associated with it. Random errors depend on the precision of the experimental measurements and are propagated to the precision of the final models. Systematic errors and mistakes often result from errors in the interpretation of the experimental data and relate directly to the accuracy of the final structure models. For example, in NMR spectroscopy errors can be introduced by misassignment of the spectral signals; in x-ray crystallography errors are most likely made when the protein structure is positioned in the electron density [1,2].

Several studies have shown that not all experimentally determined biomolecular structure models are of equally high quality [3–6]. Many different types of errors can be identified in protein structures, ranging from too tightly restrained bond lengths and angles, to molecules exhibiting a completely incorrect fold. Where the former type of errors often does not have large consequences for the analysis of the structure and typically can be easily remedied by refinement in a proper force field [7,8], the latter renders a structure model completely useless for all practical purposes. Throughout the years several such errors have been uncovered in the Protein Data Bank (PDB) [9], which often resulted in the replacement of the incorrect models with improved ones.

A typical example of an incorrectly folded structure model is the first crystal structure of photoactive yellow protein. The structure was solved initially in 1989 [10] and deposited under the now obsolete PDB entry 1PHY. An updated model released 6 y later showed that in the original model the electron density had been misinterpreted [11] (PDB entry 2PHY). Similar chain tracing problems led to an incorrect
Errors in NMR Structures

Synopsis

Three-dimensional biomolecular structures provide an invaluable source of biologically relevant information. To be able to learn the most of the wealth of information that these structures can provide us, it is of great importance that the quality and accuracy of the protein structure models deposited in the Protein Data Bank are as high as possible. In this work, the authors describe an analysis that illustrates that this is unfortunately not the case for many protein structures solved using nuclear magnetic resonance spectroscopy. They present an example in which two strikingly different models describing the same protein are analyzed using commonly available structure validation tools, and the results of this analysis show one of the two models to be incorrect. Subsequently, using a large set of recently determined structures, the authors demonstrate that unfortunately this example does not stand on its own. The analyses and examples clearly illustrate that relying solely on the experimental data to evaluate structural quality can provide a false sense of correctness and the combination of multiple sophisticated structure validation tools is required to detect the presence of errors in protein nuclear magnetic resonance structures.

model for a DD-peptidase [12] (the now obsolete PDB entry 1PTE), which was corrected 10 y later when the structure was solved again but now at higher resolution [13] (PDB entry 3PTE).

Also, for structures determined using NMR spectroscopy, cases are known where reevaluation of the experimental data, often prompted by publication of a corresponding structure, has resulted in the replacement of structures in the PDB. A well-known example is the original NMR structure of the oligomerization domain of p53 [14]. In this dimer of dimers, a difference in the orientation of the two dimers was observed between the NMR and crystal structure, the latter published shortly after the NMR structure [15] (PDB entry 1C26). Reexamination of the nuclear Overhauser enhancement (NOE) data led to the identification of three misinterpreted peaks in the original p53 NOE assignments and the inclusion of several new NOEs, resulting in a revision of the original PDB entry [16] (PDB entry 1OLH). A similar low number of misinterpreted NOE signals (17 in total) resulted in a largely incorrect fold for the anti-σ factor AsiA [17] (the now obsolete PDB entry 1KA3). In this case, it was not until a second solution structure of AsiA was published [18] (PDB entry 1JR5) that the experimental data of the original AsiA structure were reexamined and the assignment errors were discovered [19] (updated PDB entry 1TKV).

In this paper, we describe a detailed analysis of two recently released NMR structures of the protein dynein light chain 2A (DLC2A), one from human (PDB entry 1TGQ) and one from mouse (PDB entry 1Y4O). Both structures originate from large structural genomics initiatives: the structure of human DLC2A (hDLC2A) was determined by the Northeast Structural Genomics Consortium (NESGC, http://www.nesg.org), and the mouse variant (mDLC2A) was determined by the Center for Eukaryotic Structural Genomics (CESG, http://www.uwstructuralgenomics.org). Despite 96% sequence identity, large structural differences are observed between the two ensembles; an unexpected and extremely unlikely result. Using the deposited experimental data we show that only the 1Y4O structure ensemble is correct. Subsequently, we analyze both ensembles using various structure and data validation methods to show that the erroneous structure ensemble could have been identified prior to deposition. Finally, we validate a large set of protein NMR structures that were released from the PDB in the period 2003 to 2005 and show that the DLC2A example does not stand on its own, but that more errors of this magnitude can be found. We conclude with some suggestions on how, in the future, such large errors can be identified during the structure determination process using readily available validation software.

Results/Discussion

Our interest in DLC2A originated from a request by one of our collaborators to build a homology model for this protein. A BLAST search in February 2005 [20] against the PDB revealed that construction of a homology model should be straightforward: two NMR structures of DLC2A (PDB entries 1Y4O and 1TGQ), both with more than 95% sequence identity to the target sequence, had been released in the months prior to our query. Surprisingly, a first visual inspection of both structures revealed striking differences, as shown in Figure 1.

It is immediately obvious that DLC2A forms a dimer in the 1Y4O structure models (Figure 1C), whereas the 1TGQ ensemble contains DLC2A in monomeric form (Figure 1D). Additionally, the DLC2A models feature remarkably different folds. The central α-helix (α2 in Figure 1A and 1B), which extends from Asn44 to Ile68 in the 1Y4O ensemble, consists in the 1TGQ ensemble of two separate, almost antiparallel, α-helices (Thr46-Ser52 and Phe57-Thr64) connected by a turn-like region (Leu53-Ser56). Beta strands β3 (Leu71-Ser80) and β4 (Glu85-Pro90) pack tightly against each other in the 1Y4O structure models. In the 1TGQ structures, the β3 region forms a hairpin-like structure, and the β4 strand is much less tightly packed against the core of the protein.

During evolution, protein structure has always been more stable and has changed much slower than the associated sequence [21]. As a result, similar sequences fold into practically identical structures and remotely related sequences still adopt similar folds [22]. An accurate limit for this rule was recently derived by Rost [23], who found that two sequences that share over 30% sequence identity in 100 aligned residues are practically guaranteed to have the same fold. Given this knowledge, it is extremely unlikely for mouse and human DLC2A, which share 96% sequence identity, to fold into different structures shown in Figure 1C and 1D.

Visual inspection of the two ensembles made us realize quickly that the large differences probably originate from the oligomeric state of the two structures. Using NMR spectroscopy (and in most structural genomics initiatives [24]), the presence of tertiary structure in a soluble protein is typically assessed using a proton-nitrogen correlation (15N-HSQC) spectrum [25]. The observed pattern of dispersed signals, ideally one for each amino acid, provides a “fingerprint” of the protein. However, the formation of a symmetric dimer, as shown in Figure 1A, does not result in a doubling of the number of observed NMR signals. Consequently, it is not straightforward to determine the oligomeric state of a protein from its 15N-HSQC NMR spectra alone, and typically assessments have to be made from estimates of the protein’s relaxation rates [26]. Therefore, if the oligomeric state of a protein is not known or is incorrectly known, the NMR
spectra of a dimeric protein could be easily interpreted as originating from a monomer. Below, we present evidence that such a misinterpretation is the root-cause of the observed differences between the human and mouse DLC2A structure ensembles.

Figure 1C shows that the two α2-helices in the dimer interface are oriented in an antiparallel fashion. As a result, intermolecular signals arising from, for example, contacts between the N-terminal and C-terminal sides of these respective helices are to be expected. When it is a priori known that the protein under investigation is a dimer, specific experiments can be performed to distinguish such intermolecular contacts from the intramolecular ones [27]. However, if the intermolecular contacts are wrongly interpreted as intramolecular, the residues involved would appear to be close to each other also in the monomeric structure, something that is indeed observed in the structure models shown in Figure 1D.

To further test this hypothesis, we used the experimental NMR restraints from the 1Y4O structure ensemble (as those for the 1TGQ ensemble were not available) and changed all 72 intermolecular NOEs into 36 intramolecular distance restraints. With this simulated subset of 36 erroneous intermolecular NOEs (hereafter referred to as the 1TGQsim dataset) and the experimentally observed intramolecular restraints, structure calculations were performed. An ensemble of 20 structures without any distance violations larger than 0.5 Å was readily obtained. The refined geometric average of this ensemble is shown in Figure 1E, and it exhibits a fold very similar to that observed for the 1TGQ ensemble. These results provide a strong indication that the NMR spectra of hDLC2A were indeed interpreted as those of a monomer, while the protein, like its mouse homolog, is actually a dimer in solution. Conclusive evidence that the human DLC2A protein does indeed form a dimer was obtained from the NESGC Web site, where the aggregation screening records associated with hDLC2A clearly show that this protein forms dimers in solution (http://spine.nesg.org/buffer_exchange.pl?id=HR2106). During the reviewing process of this paper, one of the referees pointed us to the publication of an independent structure determination of the human homolog in August 2005 (PDB entry 1Z09) [28], which was indeed also solved as a dimer. Subsequently, in November 2005, 1.5 y after its original deposition, the monomeric PDB entry 1TGQ was replaced by a correct dimeric structure (PDB entry 2B95).

Data and Structure Analyses

Having established the origin of the errors present in the 1TGQ ensemble, we can now ask the most important question: Could these errors have been discovered during the structure determination and validation process? To investigate this issue, the deposited structure ensembles were evaluated using common structure validation tools. In addition, both structure ensembles were refined in explicit solvent [7,8] and subsequently also included in the structure validation process. The DLC2A models of the 1Y4O ensemble were refined against the deposited NOE distance restraints and dihedral angle restraints. As mentioned before, for the 1TGQ ensemble no experimental restraints had been deposited, and therefore the intramolecular restraints as obtained from the 1Y4O dataset were used. In addition, the restraints from the 1TGQsim dataset were also included in the refinement of the 1TGQ structures. The structure validation
results for the two original and the two re-refined structural ensembles are shown in Table 1.

The 1Y4O ensemble demonstrates a good agreement with the experimentally deposited restraints. For the distance restraints, no violations larger than 0.5 Å are observed, for the dihedral angle restraints, we find no violations larger than 5°. Both these thresholds are widely considered as compatible with and representative for a good structure within the NMR community. As expected, the 1TGQ sim dataset of erroneous intramolecular restraints exhibits very large violations for the 1Y4O ensembles. The validation scores, as determined by the programs PROCHECK [29] and WHAT IF [30], allow us to assess the quality of the 1TGQ dataset, and the backbone normality scores remain at a very low level (below −4). Also, the 1Y4O dihedral restraints 32, 32, 4, 0 violate more than 15°. The refinement results in a considerable improvement of the PROCHECK validation scores and the percentage of residues in the most favored regions of the Ramachandran plot increases to a commonly considered acceptable score of 85.8%. Most of the WHAT IF quality Z-scores improve, but both the Ramachandran plot and the backbone normality scores remain at a very low level (below −4). Also, the 1Y4O backbone conformation does not reach the level of quality typically observed for this quality indicator after a refinement in explicit solvent [8].

All in all, our results show that an incorrectly folded NMR structure is easily refined to a good agreement with the experimental input data and acceptable PROCHECK Ramachandran plot statistics. The overall WHAT IF quality indicators identify the structure as problematic, but only the χ1/χ2/χ3/χ4 rotamer normality score is significantly worse than the 100 refined structures present in the DRESS database [8]. When judged by its overall quality parameters, it is understandable, but nevertheless worrisome, that the erroneous 1TGQ structure went unnoticed through the structure determination and validation pipeline at the NESGC. However, a more detailed inspection of the validation results shows that the problematic regions of this ensemble of structures could have been identified.

**Structure Validation on a per-Residue Basis**

One of the first and very straightforward indicators that something might be wrong with the 1TGQ structure ensemble is the large discrepancy between the predicted and observed secondary structure, as shown in Figure 1A. Modern secondary structure prediction algorithms, such as the PSIPRED algorithm [33] applied here, typically yield predictions with an accuracy of 75% to 80%. The large deviations between predicted and observed secondary structure for the α2, β3, and β4 regions justify a further detailed inspection of these parts of the protein.

Figure 2 shows the per-residue scores of the two refined ensembles for four different WHAT IF quality indicators. The refined 1TGQ ensemble exhibits lower values for the packing quality [34] (see Figure 2A) compared to the refined 1Y4O.

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<table>
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<th>1TGQ (Original)</th>
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*Percentage of residues present in the four different regions of the Ramachandran plot.

bA Z-score [31,32] is defined as the deviation from the average value for this indicator observed in a database of high-resolution crystal structures, expressed in units of the standard deviation of this database-derived average. Typically, Z-scores below a value of −3 are considered poor, those below −4 are considered bad.

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ensemble, most notably in the a2, b4, and b5 regions. When the packing quality scores of 1TGQ are evaluated by themselves, the problematic regions do not particularly stand out. The same notion holds for the rotamer normality Z-scores (see Figure 2C), although the continuous stretch of residues from Pro45 to Arg80 with relatively low-quality scores should be considered suspicious. This is also expressed in the lower overall rotamer normality score, as already shown in Table 1. A nearly identical stretch of low scoring residues (from Met55 to Ile85) is observed when evaluating the Ramachandran plot quality scores (see Figure 2B). The finding that similar regions of consecutively low scoring residues are highlighted by different quality indicators provides more circumstantial evidence of the underlying problems, but again, no exceptional outliers are found.

Our analysis shows that only the backbone normality score unambiguously identifies the erroneous regions in the 1TGQ structure ensemble. Figure 2D shows the number of occurrences of the local backbone conformation of each residue in WHAT IF’s nonredundant internal database. For NMR structures, it is quite common to find low backbone normality scores in loops and other flexible regions, as evidenced by the validation results of the 1Y4O ensemble where most low scoring regions are found between the different secondary structure elements. These low scoring loops do, however, not influence the overall backbone normality score, which for the 1Y4O structures falls well within the normal range (Table 1).

Regular secondary structure elements, such as a-helices, typically score very well on the backbone normality check (e.g., the a1 region in both ensembles and the a2 region of 1Y4O). In the 1TGQ ensemble, however, unusually low backbone normality scores are observed for most residues in the a2 region. A near-zero number of hits is obtained for several residues (e.g., Met54, His55, Leu59, and Ser63), most of which are involved in bending the a2-helix. Alarming are the successive residues Thr75-Arg80, which all have a backbone occurrence score of 0, indicating that no similar backbone conformations are observed in the WHAT IF internal database of high-quality crystal structures [35]. This is not uncommon for occasional residues in loops but highly unlikely for consecutive residues in a well-defined region of the structure and is indicative of either a very unique or a very wrong backbone conformation. In either case, these results indisputably warrant an in-depth investigation of these regions of the structure and the experimental data that define them.

To assess if the experimental data also indicate the same regions as problematic, the sum of the NOE violations per residue is shown in Figure 2E. The found violations are small and would under normal circumstances not be considered problematic, but again they are clustered in the a2/b3 region. To further investigate this finding, we also analyzed the dataset constructed for the 1TGQ ensemble using the QUEEN program [36]. Using a representation of the structure in distance space and concepts derived from information theory, QUEEN can quantify the information contained in both individual restraints and sets of restraints. For the 1TGQ dataset, the total information content (I_total) and, for each of the individual restraints, the unique information content (Iunic) and the average information content (Iave) were determined. We previously showed that combining the unique and average information content can be very useful in the identification of problematic restraints in an experimental dataset [36]. The Iunic/Iave plot shown in Figure 3 clearly illustrates the varying information content of the different restraints in the 1TGQ dataset. Similar to previous work [37], we evaluated the 30 most important and most informative restraints, all located above the dashed line in Figure 3. In total, 13 of the 30 most crucial restraints (indicated by the black squares in Figure 3) are located in regions of the structure ensemble that score low on the backbone normality check. As such, an analysis of the 1TGQ dataset using QUEEN would also have highlighted the a2 and b3 regions as parts of the molecule deserving further investigation.

In summary, our analyses of both the structure ensemble and the supposedly observed experimental data of PDB entry 1TGQ clearly reveal the erroneous regions present in this set of
structural models. Such a severe error therefore should not have gone undiscovered in any structure determination project.

Evaluation of a Large Set of Recent NMR Structures

The fact that the erroneous 1TGQ ensemble made it into the PDB inevitably raises the question if more comparatively large errors might have gone unnoticed. To answer this question, we performed a quality analysis of a large set of protein NMR structures, the results of which are shown in Figure 4. The presented dataset was constructed by selecting from the PDB all NMR structures that were deposited after January 2003, consisted of at least 45 amino acids, and had more than 40% of their amino acids involved in secondary structure elements. The latter criterion was imposed to remove the models of largely unfolded structures that might bias our analysis. From this set all structural genomics target were filtered (310 in total), their quality scores are shown in orange in Figure 4. From the remaining NMR structures, originating from individual structure determination laboratories, an equally sized random selection of structures was made, whose quality scores are shown in green in Figure 4. For comparison, the average quality scores of the 1TGQ ensemble, both before and after refinement, are also indicated.

The data show no significant difference between the distributions of the quality indicators of structural genomics structures compared to those structures originating from individual research groups. In general, the distribution of the quality scores appears to be somewhat narrower for the structural genomics structures, but the average scores are similar, a result in-line with recent other studies [38].

The plot in Figure 4 illustrates the spread of quality scores of the entire dataset. The distribution of outliers outside the normal 90th, 75th and 50th percentiles of the data points for each quality indicator is indicated using colored data points. The quality scores of the original and refined 1TGQ ensemble (cf. Table 1) are indicated by red and blue crosses, respectively. The backbone normality score of 1TGQ is identical for the original and refined ensemble.

The data show no significant difference between the distributions of the quality indicators of structural genomics structures compared to those structures originating from individual research groups. In general, the distribution of the quality scores appears to be somewhat narrower for the structural genomics structures, but the average scores are similar, a result in-line with recent other studies [38]. Surprisingly, for both the packing and Ramachandran plot quality scores, the 1TGQ ensembles score comparable to the majority of the NMR structures. The rotamer normality score initially places the 1TGQ ensemble among the 10% worst scoring structural genomics structures, but after refinement it is amidst the top 10%. As before, the backbone normality score consistently identifies the erroneous 1TGQ structures as one of the outliers. Given the serious errors present in the 1TGQ ensemble, one might consider the fact that several NMR structures solved over the past years demonstrate backbone normality scores lower than those of 1TGQ rather worrisome.

Visual inspection of the structural ensembles exhibiting lower backbone normality scores than 1TGQ revealed that in some instances these low scores resulted from the corresponding proteins exhibiting unusual folds or dynamic behavior. For others, however, we noted some striking structural abnormalities of which we will discuss two examples. First, our attention was drawn to the NMR structure with the lowest backbone normality score (Z = –9.8). It corresponds to an alternatively spliced PDZ domain of PTP-Bas [39] (PDZ-Bas, PDB entry 1Q7X), which was determined in the context of the Structural Proteomics In Europe project (SPINE, http://www.spineurope.org). In this structure ensemble, an arginine side chain deeply penetrates the hydrophobic core (cf. Figure 5A). Arginine, however, is a very hydrophilic residue and is typically not observed in hydrophobic environments. In the highly identical alternative spliced second PDZ domain of PTP-BL [37] (PDZ-BL, PDB entry 1OZL), sequence identity 95% with PDB entry 1Q7X)
and, to the best of our knowledge, in all other homologous PDZ domains, the corresponding arginine is indeed solvent exposed (cf. Figure 5B), rendering it very unlikely for the IQTX ensemble to be correct. This finding is corroborated by the backbone residual dipolar coupling (RDC) data [40] measured for the PDZ-BL protein [37]. To allow for a fair comparison, an ensemble of 20 PDZ-BL structures was calculated and refined using only the experimental distance and dihedral data and the procedures described above, as the deposited structures [37] were refined against the RDC restraints. The RDC R-factor [41] obtained for the newly calculated PDZ-BL ensemble is 43%, whereas the RDC R-factor of 69% for the PDZ-BS ensemble is significantly higher. This clearly demonstrates the ability of RDC-derived orientational restraints to also distinguish incorrect backbone orientations, but unfortunately these data are typically not acquired in structural genomics pipelines.

As a second example, we noticed striking differences between the apo- and copper bound restraints, even a largely incorrect structure is readily refined to seemingly acceptable levels of quality. As a result, the quality of biomolecular NMR structures cannot be safely assessed by the size and number of residual restraints violations, the precision of the structure ensemble, or even the fact that most residues are located in the allowed regions of the Ramachandran plot. Relying solely on these indicators to evaluate an ensemble of NMR structures therefore provides a false sense of correctness. The fundamentally different nature of residual dipolar couplings renders them complementary to traditional NMR data and a powerful tool to identify large errors in NMR structures. Unfortunately, in
many instances, such as in most structural genomics efforts, they are not routinely acquired and proper use of structure validation tools then becomes crucial. Furthermore, our results show that also more sophisticated quality indicators, e.g., the overall WHAT IF backbone normality score, do not unambiguously identify problematic structures. In contrast, we showed that only the simultaneous evaluation of multiple quality indicators on a per-residue basis, however, combined with a careful evaluation of the experimental data (e.g., using QUEEN), does allow for the well-supported identification erroneous regions in biomolecular NMR structures, thereby avoiding errors as those reported here.

Materials and Methods

NMR structures and data. For both mDLC2A and hDLC2A, the structure ensembles were obtained from the PDB (PDB entries 1Y4O and 1TGQ, respectively). The residue numbering of the 1TGQ ensemble was adjusted to that of the 1Y4O ensemble, as shown in Figure 1. The coordinates describing the His-tag in the 1Y4O ensemble (residues 1 to 8) were removed so that all DLC2A models contained an equal number of residues.

The experimental restraints for the 1Y4O ensemble, solved as a dimer, were obtained from the PDB, for the 1TGQ ensemble no experimental restraints were available at the time of writing. All stereospecifically assigned NOEs were designed for the violation analysis of structure calculations, and refinements. To be able to use the same dataset to both structures, all restraints involving unique atoms of the three amino acids that are different in both sequences were transported to both structures, all restraints involving unique experimental restraints were available at the time of writing. All dimer, were obtained from the PDB, for the 1Y4O ensemble no NOEs were assigned for the His tag.

The coordinates describing the His-tag in the structure ensembles were obtained from the PDB (PDB entries 1Y4O and 1TGQ, respectively). The deposited and constructed datasets were evaluated using the QUEEN program [36].

Supporting Information

Accession Numbers

The UniProt (Universal Protein Resource) [40] accession numbers for mDLC2A and hDLC2A are P62627 and Q9NP97, respectively.

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Competing interests. The authors have declared that no competing interests exist.