OPINION ARTICLE

Quality of histone modification antibodies undermines chromatin biology research [version 2; peer review: 3 approved]

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Abstract
Histone post-translational modification (PTM) antibodies are essential research reagents in chromatin biology. However, they suffer from variable properties and insufficient documentation of quality. Antibody manufacturers and vendors should provide detailed lot-specific documentation of quality, rendering further quality checks by end-customers unnecessary. A shift from polyclonal antibodies towards sustainable reagents like monoclonal or recombinant antibodies or histone binding domains would help to improve the reproducibility of experimental work in this field.

Keywords
histone modifications, antibodies, recombinant proteins, quality control

This article is included in the Antibody Validations gateway.

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2. Scott B. Rothbart, Van Andel Institute, Grand Rapids, USA
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Any reports and responses or comments on the article can be found at the end of the article.
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The lack of reproducibility is widely recognized as a serious issue in contemporary research (see (Buck, 2015; Freedman & Inglese, 2014; Freedman et al., 2015; McNutt, 2014a; McNutt, 2014b) and the Nature special “Challenges in irreproducible research” April 2, 2013). In molecular biology, the quality of antibodies has been identified and highlighted as one of the most recurring stumbling blocks that undermine the quality and validity of experimental results (Baker, 2015; Bordeaux et al., 2010; Bradbury & Pückthun, 2015a; Bradbury & Pückthun, 2015b). This issue is even more pervasive in the field of molecular epigenetics and chromatin biology, where antibodies for various types of histone post translational modifications (PTMs) have been single-handedly used to translate the language of histone modifications into experimentally observable properties. Because of this, most of what we know about the distribution, role and function of histone modifications so far has been passed through an antibody as essential mediator.

Raising a specific histone modification antibody is not a trivial task; this is mostly due to the hypermodified state of the histone tail, coupled with the minute size and the chemical relatedness of many histone modifications and similarities in the amino acid sequence of the modified residues. The antibody has to be able to discriminate between the unmodified and the modified state of the targeted amino acid residue, as well as between different forms of modifications (e.g. acetylations of different lysine residues, mono-, di- and trimethylation of lysine residues, or symmetric and asymmetric methylation of arginine residues). Moreover, the presence of an adjacent modification might prevent binding of an antibody to the target modification, causing false negative results. In addition, the antibody should bind the modified amino acid residue only at defined modification sites on the target protein, which implies that not only the modification but also the amino acid sequence must be recognized. This is particularly difficult for some histone modifications such as methylation or acetylation of H3K9 and H3K27 which occur within an identical amino acid context (ARKS motif) and make the readout of the target peptide sequence outside of this central motif vital as well.

In spite of the intricate task of producing histone modification antibodies and their crucial role in chromatin biology, surprisingly, they remain insufficiently characterized. In line with this, numerous scientific groups have alarmingly raised concerns about the promiscuous behavior of some histone modification antibodies and undocumented effects of secondary modifications (Bock et al., 2011; Egelhofer et al., 2011; Hattori et al., 2013; Kungulovski et al., 2014; Nishikori et al., 2012; Rothbart et al., 2015). As mentioned above, the situation in chromatin biology is exceptional, because of the role of histone PTM antibodies as the sole research tool in this field. As a consequence, elaborate quality control criteria for histone PTM antibodies were put forward to ensure the integrity of research (Egelhofer et al., 2011; Kungulovski et al., 2015; Landt et al., 2012). To increase transparency, at least two databases for deposition of antibody quality data from researchers were put in place (http://compbio.med.harvard.edu/antibodies/; http://www.histoneantibodies.com/) (Egelhofer et al., 2011; Rothbart et al., 2015). However, in spite of being heroic attempts, these and similar databases have only a limited value, because most of the antibodies used in chromatin biology are polyclonal, and lab experience over the last years has demonstrated that the specificity data obtained for one batch of antibody do not necessarily reflect the properties of another one (Kungulovski et al., 2014), a caveat which is still often ignored by naïve end-users. Related to this the practice of some antibody manufactures of retaining catalog numbers for new polyclonal antibody lots is unacceptable and misleading as well as the practice to use historical data sheets for antibodies to which they do not apply (Voskui, 2014).

The necessary quality control steps for histone modification antibodies (Egelhofer et al., 2011; Kungulovski et al., 2015; Landt et al., 2012) currently burden the individual antibody user with high costs and workload. Given that antibodies are expensive reagents, which are of no use without appropriate quality documentation, these efforts must be redirected from the end-customer to the manufacturers of antibodies. Herein, we urgently ask the vendors and manufacturers of antibodies to provide the necessary product sheets for all types of antibodies on a regular basis, including quality control documentation for each batch of polyclonal and each catalog number of recombinant or monoclonal antibodies. Results of the following validation tests must be provided to enable the end-user finding the information, which is particularly relevant for the intended application of an antibody:

1. Combinatorial profiling of specificity with peptide arrays or similar high-throughput methods. If possible, profiling of specificity with recombinant and semisynthetic nucleosomes harboring different modifications.
2. Western blot results with native (as positive control) and recombinant histones (as negative control).
3. Western blot results with native histones or nuclear extracts from cells where the responsible histone modifying enzyme has been deleted or depleted (mammalian cells) or mutant histones (yeast).
4. Reproducibility of ChIP-seq data and high correlation with similar validated ChIP-seq datasets.

As proposed by others (Bradbury & Pückthun, 2015a; Bradbury & Pückthun, 2015b) end-users should consider boycotting companies not complying with this demand, or at least stay away from products lacking a proper lot-specific documentation. While one may expect...
that better quality control will increase the prices of commercial antibodies, end-customers will not be forced to conduct their own quality control and they will not waste money for non-functional antibodies, so that the overall final costs may not be much higher. Moreover, the value of the obtained data will increase massively with better antibody validation.

The batch-to-batch variability of critical properties like cross-reactivity or inhibition by secondary marks makes the application of polyclonal antibodies intrinsically unsustainable, because experiments cannot be reproduced after the corresponding batch of an antibody is sold out. As a consequence of this, rigorously speaking, large data sets in chromatin biology exist in a “grey” area outside of natural science, since it is impossible to repeat the underlying experiments. In a long-term perspective, a shift away from polyclonal antibodies towards alternative reagents, which can be produced at constant quality, would help to reduce the necessary financial and workload efforts associated with quality control of polyclonal antibodies and ensure sustainability (Bradbury & Plückthun, 2015a; Bradbury & Plückthun, 2015b). This applies to high-quality monoclonal antibodies, recombinant antibodies (Hattori et al., 2013) or analogous recombinant reading domains (Kungulovski et al., 2014). This will not only help to reduce costs in chromatin research in the long run (once obtained, the documentation will be valid for all lots) but also help to standardize the affinity reagents used and ease the lab-to-lab comparison of data. The recombinant reagents are particularly promising, because their sequences can be published, which ensures full transparency and reproducibility. Of note, in chromatin biology native reading domains designed by nature to specifically recognize relevant histone PTM marks are available as an alternative to antibodies (Kungulovski et al., 2014), which is an advantage over other fields, where recombinant production of antibodies is the only technical solution to the issue of reproducible performance and long term availability of these essential research reagents.

Author contributions
GK and AJ wrote the paper. All authors have seen and agreed to the final content of the manuscript.

Competing interests
The authors declared no competing interests.

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I confirm that the funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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The authors concentrate on their core message for better characterization and documentation and for shifting toward renewable reagents. It is important to note that more characterization would be better but demanding the inclusion of assays of limited predictive power would increase the cost of antibodies without substantially benefiting the end users.

"Moreover, we are not convinced that the development of special conditions by each lab is an advisable development, because in many cases these may not be fully documented which - again - would undermine reproducibility. While it is self-evident that the researchers are ultimately responsible for the validity of all their results, lab internal quality certifications in our view are not the best way to proceed in an ever growing experimental field."

This is not what meant in my review. Instead, I mean that what an end user studies would always represents novel conditions (different cells, different culture conditions, different number of cells, etc.). So, strictly speaking, there is no guarantee that even a highly validated antibody functions in the actual experiment. The field would benefit greatly by establishing better internal controls that are included in each experiment, particularly for ChIP.

**Competing Interests:** No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.
Andrew Bradbury  
Bioscience Division, Los Alamos National Laboratory, Los Alamos, NM, USA  
The authors have addressed my concerns

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.
support and binding of dilute antibody samples is detected. To state the obvious, IP-type methods are suited for validating antibodies for IP-type applications (IP, ChIP), whereas blotting-type methods are suited for validating antibodies for blotting-type applications (Western, immunostaining).

Potential problems arise when the validation format is different from the application format. It is not easy to predict whether antibodies validated using blotting-type methods perform well in IP-type applications such as ChIP, and vice versa. Egelhofer et al. (2011) reported that more than 20% of antibodies that have been validated to be specific in peptide blots still fail in ChIP experiments. In typical IP applications where an antibody is immobilized on a solid support, antibody affinity is a critical parameter. In contrast, affinity is not critical in blotting type applications, because the bivalent format of the conventional antibody (i.e. two antigen-binding sites per molecule) helps boost binding (the so-called avidity effect). Indeed, it has been found that an antibody that looked good on peptide arrays performed poorly in IP and conversely another antibody that did not look good on peptide arrays performed exceedingly well in IP (Nishikori et al., 2012). Similarly, an antibody (Active Motif 39156) performed well in IP validation using semi-synthetic nucleosomes ("IceChIP"), although it appeared cross-reactive in peptide-array validation and in Western blotting (Rothbart et al., 2015). Further complications arise from the fact that spot intensities in array-type experiments are not quantitatively correlated with the strengths of the measured interactions (see, for examples, Stiffler et al., 2006; Hause et al. 2012).

Another omission is that validation and actual results depend on experimental conditions and accordingly an antibody validated under one set of conditions may not perform as well under a different set of conditions. Practitioners of immunoblotting are all familiar with the need for "optimizing" conditions for their own experiments. Similar optimizations are needed for other types of applications for which desired outcomes are less obvious. Furthermore, the abundance of the antigen of interest relative to off targets influences the outcome. Even a highly selective and potent antibody may not sufficiently enrich extremely rare antigens. Accordingly, for IP-type applications, mass spectroscopy-based validation using IP with input materials similar to those used in actual experiments (Peach et al., 2012; Hattori et al., 2013; Marcon et al. 2015) and IP of semi-synthetic nucleosomes (Grzybowski et al., 2015) are better suited as validation methods.

This paper should emphasize more that the end user must critically evaluate limitations of validation methods caused by format mismatches and/or variations in experimental conditions. I do not agree with this paper's recommendations that a single set of information be provided with any antibody regardless of its intended use.

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**Competing Interests:** No competing interests were disclosed.

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**
but real applications deal with the pull-down of full histone tails. Moreover, we are not convinced that the development of special conditions by each lab is an advisable development, because in many cases these may not be fully documented which - again - would undermine reproducibility. While it is self-evident that the researchers are ultimately responsible for the validity of all their results, lab internal quality certifications in our view are not the best way to proceed in an ever growing experimental field.

**Competing Interests:** No competing interests were disclosed.

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**Reviewer Report**

03 November 2015

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Scott B. Rothbart  
Center for Epigenetics, Van Andel Institute, Grand Rapids, MI, USA

Antibody reliability in biomedical research is of utmost importance. The quality of these reagents in chromatin biology applications is of particular concern given their position as essential tools for most techniques characterizing the cellular abundance and genomic distribution of histone post-translational modifications (PTMs).

I agree with the Kungulovski and Jeltsch that increased accountability needs to be demanded from companies who sell histone PTM antibodies, and their four recommended quality control measures are reasonable expectations. In addition, it should also be noted that the practice of retaining catalog numbers for new polyclonal antibody lots is unacceptable and misleading.

Moreover, and particularly in light of the increased awareness of antibody concerns in the field, experimentalists and epigenome consortium leaders (e.g., ENCODE, BLUEPRINT) should be more rigorous in their own evaluation of histone PTM antibodies when choosing a reagent for their study. Antibody specificity data and lot numbers used should also be standard requests from journal editors and reviewers.

Accountability clearly needs to come from all parties if we are to continue benefiting from the use of these affinity tools in chromatin research.

**Competing Interests:** No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.
Author Response 12 Nov 2015

Albert Jeltsch, Stuttgart University, Stuttgart, Germany

• “I agree with the Kungulovski and Jeltsch that increased accountability needs to be demanded from companies who sell histone PTM antibodies, and their four recommended quality control measures are reasonable expectations. In addition, it should also be noted that the practice of retaining catalog numbers for new polyclonal antibody lots is unacceptable and misleading.”

Reply: We have added the sentence to the paper “that the practice of retaining catalog numbers for new polyclonal antibody lots is unacceptable and misleading”. Thanks a lot for this helpful suggestion.

• “Moreover, and particularly in light of the increased awareness of antibody concerns in the field, experimentalists and epigenome consortium leaders (e.g., ENCODE, BLUEPRINT) should be more rigorous in their own evaluation of histone PTM antibodies when choosing a reagent for their study. Antibody specificity data and lot numbers used should also be standard requests from journal editors and reviewers. Accountability clearly needs to come from all parties if we are to continue benefiting from the use of these affinity tools in chromatin research.”

Reply: We like to mention, that in our view more responsibility in structured product documentation lies at the side of the supplier. Quality checks done by end-customers are an emergency action, but they will not solve the problem of long-term and lab-to-lab reproducibility. Also they put all financial pressure on the end customer or a product, which is not common practice in other parts of the economy.

Competing Interests: No competing interests were disclosed.

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Andrew Bradbury
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Paragraph 2 should also indicate that antibodies purportedly recognizing PTMs at specific sites, need to have their recognition specificity also tested against the same PTM at different sites, in the same protein, or others, and with the same core sequence or others. Many so-called specific phosphotyrosine antibodies actually recognize the phosphotyrosine modification independently of...
its sequence context.

"In spite of the intricate task of producing histone modification antibodies and their crucial role in chromatin biology, surprisingly, they remain to be insufficiently characterized" should be changed to "In spite of the intricate task of producing histone modification antibodies and their crucial role in chromatin biology, surprisingly, they remain insufficiently characterized"

"the specificity data obtained for one batch of antibody do not necessarily reflect the properties of another one" Voskuil (Commercial antibodies and their validation. Version 2. F1000Res. 2014 Oct 2 [revised 2014 Oct 15]:3:232. doi: 10.12688/f1000research.4966.2. eCollection 2014) describes the relatively unknown practice of some antibody manufacturers to use historical data sheets for antibodies to which they do not apply. This should also be mentioned and cited.

The recommendations in paragraph 4 are commendable. However, if manufacturers are expected to carry this out on every lot they sell, the author must acknowledge that the cost of antibodies will have to increase.

"As proposed by others (Bradbury & Pluckthun, 2015) end-users should consider boycotting companies not complying with this demand, or at least stay away from products lacking a proper lot-specific documentation." Actually, this was not our main proposal. Our main point (amplified in Getting to reproducible antibodies: the rationale for sequenced recombinant characterized reagents. Bradbury AR, Plückthun A. Protein Eng Des Sel. 2015 Oct;28(10):303-5. doi: 10.1093/protein/gzv051) was that we should move away from the use of polyclonal antibodies altogether and use only well characterized sequenced recombinant antibodies. Only in this way can we ensure antibody reproducibility.

In the last paragraph, the author indicates that recombinant antibodies (or other proteins) may solve this problem. However, this will only be the case if such binders can be unequivocally identified, which will only occur if sequences can be referred to unambiguously. Otherwise, as antibody companies are bought and sold, catalog numbers will change and it may become difficult to reproduce experiments, because it will not be clear which original antibody was used.

**Competing Interests:** No competing interests were disclosed.

**I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.**

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Author Response 12 Nov 2015

Albert Jeltsch, Stuttgart University, Stuttgart, Germany

- “Paragraph 2 should also indicate that antibodies purportedly recognizing PTMs at specific sites, need to have their recognition specificity also tested against the same PTM at different sites, in the same protein, or others, and with the same core sequence or others. Many so-called specific phosphotyrosine antibodies actually recognize the phosphotyrosine modification independently of its sequence context.”
Reply: We agree. This point was mentioned in paragraph 2 on p. 2 using methylation at H3K9 and H3K27 as an example. “Another difficulty is that some histone modifications such as methylation or acetylation of H3K9 and H3K27 lie within an identical amino acid context (ARKS motif), which makes the readout of the target peptide sequence outside of this central motif very important as well.” We have modified this paragraph to make the point clearer and better reflect what the reviewer was asking for: “Moreover, the antibody should bind the modified amino acid residue only at defined modification sites on the target protein, which implies that not only the modification but also the amino acid sequence must be recognized. This is particularly difficult for some histone modifications such as methylation or acetylation of H3K9 and H3K27 which occur within an identical amino acid context (ARKS motif) and make the readout of the target peptide sequence outside of this central motif vital as well.”

○ “In spite of the intricate task of producing histone modification antibodies and their crucial role in chromatin biology, surprisingly, they remain to be insufficiently characterized” should be changed to “In spite of the intricate task of producing histone modification antibodies and their crucial role in chromatin biology, surprisingly, they remain insufficiently characterized”

Reply: This has been changed as proposed.

○ “The recommendations in paragraph 4 are commendable. However, if manufacturers are expected to carry this out on every lot they sell, the author must acknowledge that the cost of antibodies will have to increase.”

Reply: Please note in the original manuscript on p. 2 we stated that a shift to sustainable reagents (i.e. away from polyclonal antibodies) “would help to reduce the necessary financial and workload efforts associated with quality control of polyclonal antibodies and ensure sustainability”, which partially addressed this point. We now added an additional sentence stating “While one may expect that better quality control will increase the prices of commercial antibodies, end-customers will not be forced to conduct their own quality control and they will not waste money for non-functional antibodies, so that the overall final costs may not be much higher.” to incorporate this request more explicitly.

○ “As proposed by others (Bradbury & Pluckthun, 2015) end-users should consider boycotting companies not complying with this demand, or at least stay away from
products lacking a proper lot-specific documentation." Actually, this was not our main proposal. Our main point (amplified in Getting to reproducible antibodies: the rationale for sequenced recombinant characterized reagents. Bradbury AR, Plückthun A. Protein Eng Des Sel. 2015 Oct;28(10):303-5. doi: 10.1093/protein/gzv051) was that we should move away from the use of polyclonal antibodies altogether and use only well characterized sequenced recombinant antibodies. Only in this way can we ensure antibody reproducibility.”

Reply: We have added the citation to this very insightful paper now also at the corresponding place in our manuscript and also added the Prot. Eng. Des. Sel. reference. “As already proposed, in a long-term perspective, a shift away from polyclonal antibodies towards alternative reagents, which can be produced at constant quality, would help to reduce the necessary financial and workload efforts associated with quality control of polyclonal antibodies and ensure sustainability (Bradbury & Plückthun, 2015, Nature 518, 27-29; Bradbury & Plückthun, 2015, Prot. Eng. Des. Sel. 28, 303-305).”

○ “In the last paragraph, the author indicates that recombinant antibodies (or other proteins) may solve this problem. However, this will only be the case if such binders can be unequivocally identified, which will only occur if sequences can be referred to unambiguously. Otherwise, as antibody companies are bought and sold, catalog numbers will change and it may become difficult to reproduce experiments, because it will not be clear which original antibody was used.”

Reply: This is a valid point. We have added on sentence to stress this: “The recombinant reagents would be particularly promising, because their sequences can be published, which ensures full transparency and reproducibility.”

**Competing Interests:** No competing interests were disclosed.
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