Joint Binding of OTX2 and MYC in Promotor Regions Is Associated with High Gene Expression in Medulloblastoma


Published in:
PLoS One

DOI:
10.1371/journal.pone.0026058

Citation for published version (APA):
Joint Binding of OTX2 and MYC in Promotor Regions Is Associated with High Gene Expression in Medulloblastoma

Jens Bunt, Nancy E. Hasselt, Danny A. Zwijnenburg, Jan Koster, Rogier Versteeg, Marcel Kool

Department of Oncogenomics, Academic Medical Center, Amsterdam, The Netherlands

Abstract

Both OTX2 and MYC are important oncogenes in medulloblastoma, the most common malignant brain tumor in childhood. Much is known about MYC binding to promoter regions, but OTX2 binding is hardly investigated. We used ChIP-on-chip data to analyze the binding patterns of both transcription factors in D425 medulloblastoma cells. When combining the data for all promoter regions in the genome, OTX2 binding showed a remarkable bi-modal distribution pattern with peaks around −250 bp upstream and +650 bp downstream of the transcription start sites (TSSs). Indeed, 40.2% of all OTX2-bound TSSs had more than one significant OTX2-binding peak. This OTX2-binding pattern was very different from the TSS-centered single-peak binding pattern observed for MYC and other known transcription factors. However, in individual promoter regions, OTX2 and MYC have a strong tendency to bind in proximity of each other. OTX2-binding sequences are depleted near TSSs in the genome, providing an explanation for the observed bi-modal distribution of OTX2 binding. This contrasts to the enrichment of E-box sequences at TSSs. Both OTX2 and MYC binding independently correlated with higher gene expression. Interestingly, genes of promoter regions with multiple OTX2 binding as well as MYC binding showed the highest expression levels in D425 cells and in primary medulloblastomas. Genes within this class of promoter regions were enriched for medulloblastoma and stem cell specific genes. Our data suggest an important functional interaction between OTX2 and MYC in regulating gene expression in medulloblastoma.

Introduction

OTX2 encodes a homeodomain containing transcription factor, which is essential for normal brain development. In the cerebellum, OTX2 is expressed in progenitor cells, but only at pre-natal stages. In post-natal cerebellum, no OTX2 expression can be detected [1]. However, the malignant childhood brain tumor medulloblastoma, which originates in the cerebellum, often expresses OTX2 at high levels [1–5]. These high OTX2 levels are known to be indirect targets.

Although OTX2 is an essential gene in medulloblastoma, little is known about the mechanism by which OTX2 regulates the expression of its target genes. Only in a few studies interaction of OTX2 with other gene expression regulators have been reported. These studies mainly focused on the regulation of a single target gene [10–15]. Early studies used limited promoter regions or oligonucleotides to assess OTX2 binding and they identified TAATCC and related sequences as the main DNA-binding motif for OTX2 [16–21].

In this study, we have analyzed the binding of OTX2 to promoter regions in the complete genome and compared the OTX2 data with ChIP-on-chip data for MYC in medulloblastoma. MYC is another important oncogene in medulloblastoma pathogenesis and high-level amplifications of the MYC locus are significantly associated with a poor clinical outcome [22–25]. Our analyses show that 40.2% of all OTX2 bound promoter regions contain multiple OTX2-binding peaks, while the other 59.8% showed only single OTX2 binding. Together they contribute to a specific bi-modal distribution of OTX2 binding near TSSs. The distribution of OTX2-binding motifs provided a possible explanation for the bi-modal distribution as these motifs were depleted near TSSs in the genome. MYC binding displayed a distribution centered on the TSS, similar to other studies [26,27].
Both OTX2 and MYC binding to the promoter region correlated with higher gene expression. The highest expression levels were found for genes with multiple OTX2-binding peaks plus MYC binding. These genes, but not the genes with single OTX2 binding or the genes with multiple OTX2 binding and no MYC, were enriched for medulloblastoma and stem cell specific genes. Furthermore, OTX2 and MYC bind closer to each other in promoter regions than would have been expected if binding occurred randomly. Together these results suggest that OTX2 and MYC cooperate in regulating gene expression in medulloblastoma.

Results

OTX2 shows unique DNA-binding pattern in medulloblastoma cell lines

To investigate OTX2 binding, we examined where OTX2 binds in promoter regions. Data from our OTX2 ChIP-on-chip (Nimblegen promoter arrays) experiment in D425 cells were used [8]. To get a global overview of OTX2 binding we aligned all promoter regions according to the position of the transcriptional start sites (TSSs) and per bin of 50 bp we calculated the average OTX2-binding signal for all promoters together. The results revealed a bi-modal distribution of OTX2 binding in promoter regions with peaks around -250 bp upstream and +650 bp downstream from the TSSs (Figure 1A).

A similar bi-modal distribution was found when only considering the significant binding peaks (as called by the Nimblegen algorithm). We plotted these data as the percentage of all promoter regions with a significant binding peak and observed a similar bi-modal distribution (Figure 1B). The two control ChIP-on-chip experiments, in which we omitted the OTX2 antibody or used a FLAG antibody instead, did not show this pattern. A similar bi-modal distribution of OTX2 binding was also observed when we used ChIP-on-chip data of MED8A and DAOY medulloblastoma cells with ectopic OTX2 expression (Figure 1C and Figure S1) [9].

As this OTX2 binding distribution strongly differs from the TSS-centered single peak pattern commonly found for transcription factors, we performed another ChIP-on-chip experiment for MYC, which is like OTX2 also amplified and highly expressed in D425 cells (Figure S1). Data from this ChIP-on-chip experiment showed that the MYC binding, calculated over all promoter regions, is concentrated in a single peak centered on the TSS (Figure 1D), in line with previous reports for MYC in other cell systems [26,27].

To investigate whether the bi-modal distribution of OTX2 implies multiple OTX2 binding peaks per gene, we calculated the number of significant OTX2-binding peaks per promoter region. As a result, 40.2% of the 11,389 promoter regions with OTX2 binding had two or more significant OTX2-binding peaks, and the remaining 59.8% had a single OTX2-binding peak. For both single and multiple OTX2-bound promoter regions the widths of the peaks were similar. The promoter regions with multiple OTX2 binding displayed again the bi-modal distribution pattern (Figure 1E and 1F). Even when correcting for overlapping promoter regions, a bi-modal pattern remained. In single bound promoter regions, there was a less prominent bi-modal distribution (Figure 1E and 1F). However, the distribution of single OTX2-bound promoters did not resemble the MYC-binding pattern, which is TSS-centered. Therefore, the overall bi-modal distribution seems not caused by multiple OTX2 binding alone, but a general tendency of OTX2 to bind adjacent to the TSS.
different classes of OTX2-bound promoters were defined: single OTX2-bound promoter regions with or without MYC binding and multiple OTX2-bound promoter regions with or without MYC binding.

Figure 2 shows the OTX2-binding peaks for all four possible combinations of OTX2 and MYC binding to promoter regions with OTX2 binding. Two classes have single OTX2-binding peaks with or without MYC binding (Figure 2A), while the other two classes have multiple OTX2 peaks with or without MYC binding (Figure 2B). Per class the promoter regions were sorted according to the location of the first OTX2 binding peak, starting with the most upstream peak. Strikingly, when we depicted the MYC-binding peaks for these same promoter regions (Figure 2A and 2B, right panels), we observed that the MYC-binding peaks closely follow the OTX2-binding pattern. This was most clear for the class of promoter regions with single OTX2-binding peaks, but even for the class of promoter regions with multiple OTX2 binding the MYC-binding peaks tend to accumulate in the same areas. Reversely, when viewing from the MYC binding perspective, OTX2 binding follows MYC binding particularly when closer to the TSS (Figure S2). These data suggest a frequent co-localization of both transcription factors on the promoter. Furthermore, when comparing the calculated distance between OTX2 and MYC-binding peaks to the expected distance (Figure 2C) OTX2 and MYC bind closer to each other in promoter regions then expected. However, they do not occupy the exact same location. MYC preferentially binds near or at the TSS, while OTX2 binding tends to be more adjacent to the TSS.

OTX2 binding motifs are depleted near the TSSs

We investigated whether the observed bi-modal distribution of OTX2 binding relates to DNA-binding motifs. Therefore, we performed Discriminating Motif Enumerator (DME) analyses of the regions bound by OTX2 to discover binding motifs over-represented within the OTX2-binding peaks [29]. TAATCC turned out to be the most over-represented sequence, followed by the related TAAGGCC and TAATCT sequences (Table S1A). The four different promoter classes all showed a similar frequency for these sequences. These same sequences were also enriched in the OTX2-bound sequences identified in MED8A cells with overexpression of ectopic OTX2 (Table S1B). Similar analyses identified known E-box sequences as the main binding motifs in MYC-bound regions (Table S1C). All OTX2 and MYC motifs were enriched in the centers of binding peaks (Figure 3A). We also analyzed the distribution of these OTX2- and MYC-binding motifs in promoter regions. Surprisingly, all three OTX2 motifs were depleted near the TSSs, while E-box sequences were enriched (Figure 3B, blue lines). As TAATCC and related sequences are enriched in Alu repeats, these analyses were repeated with a repeat mask. However, OTX2 motifs still did not peak at the TSSs, while E-box sequences remained enriched (Figure 3B, red lines). Thus, the bi-modal distribution of OTX2 binding might be caused by the depletion of OTX2-binding motifs near the TSSs.

Binding of OTX2 and MYC is associated with increased gene expression

To assess whether OTX2 or MYC binding is related to gene expression, we depicted the OTX2- and MYC-binding peaks for each promoter region and sorted the promoter regions according to the gene expression levels as established by Affymetrix expression profiling of D425 cells [8]. Figure 4A (left panel) shows a correlation between the amount of OTX2-binding peaks and gene expression levels. The promoters of highly expressed genes showed more signal. The panel on the right in Figure 4A shows similar data for MYC. Like OTX2, MYC binding correlates with gene expression levels. This is also demonstrated in Figure 4B, in which the percentage of all promoter regions that have a OTX2- or MYC-binding peak at the indicated position are plotted. Promoter regions were divided into five categories based on increasing gene expression levels in D425 cells. For both OTX2 and MYC, the percentage of promoter regions with a binding peak increased with increasing expression levels. The bi-modal OTX2 and the TSS-centered MYC-binding patterns do not differ between the different expression categories. Thus, both OTX2 and MYC binding are associated with increased gene expression.

OTX2 binding motifs do not correlate with expression levels

As OTX2 binding correlates with gene expression, we wondered whether the usage of the different OTX2-binding motifs influenced gene expression levels. However, the more highly expressed genes showed no enrichment for any OTX2-binding motifs in their promoter regions (Figure 5). The presence of a motif also had no effect on the number of genes regulated or the magnitude of the regulation after OTX2 silencing in D425 cells (data not shown). Therefore, even though these motifs are required for OTX2 binding, additional factors seem to be necessary to determine expression levels and regulation.

Genes with multiple OTX2 and MYC binding are expressed at higher levels in medulloblastoma and stem cells

We then investigated whether the four different classes of promoter regions with OTX2 and MYC binding as depicted in Figure 2 show differences in gene expression levels. Interestingly, the most striking correlation was found for the class of promoter regions with multiple OTX2-binding peaks with MYC binding (Figure 6A; blue line). In D425 cells, with increasing expression the percentage of promoter regions that have multiple OTX2 and MYC binding also increased. Therefore, genes with a promoter region from this class were more abundant in the high expression categories. Genes with promoter regions from the other classes, i.e. with single OTX2-binding peaks with or without MYC binding or with multiple OTX2-binding peaks without MYC binding, were more or less equally distributed over all expression categories (Figure 6A). We found the same correlation between OTX2/ MYC binding and gene expression when we used expression data of medulloblastoma tumors [5,30] (Figure 6B). These results suggest that multiple OTX2 and MYC binding have a synergistic effect on gene expression.

Surprisingly, however, there was no relation between the four classes of promoter regions and gene regulation after OTX2 silencing in D425 cells [8]. The percentage of regulated genes (ranging from 15 to 18%) was more or less equal between the four classes. Furthermore, Gene ontology analyses did not reveal any differences in molecular function between the genes in these four classes. In contrast, gene set enrichment analyses (GSEA), using either DAVID [31] or the BROAD tools [32,33], revealed that genes with multiple OTX2-binding peaks and MYC binding were significantly enriched for genes associated with mouse (neuronal) stem cells [34] and human medulloblastoma [35] (Table S2). The other groups did not show such enrichments.
Finally, we investigated the relation between this class of promoter regions and medulloblastoma/stem cell specific expression. The average expression levels of genes from the class with both multiple OTX2-binding peaks and MYC binding were consistently higher in medulloblastoma and human neuronal stem cells as compared to genes from other classes (Figure 6C). This difference was not present in normal cerebellum. These data suggest that genes with multiple OTX2-binding peaks and MYC binding in their promoter region may have specific functions in medulloblastoma and/or stem cells.

**Discussion**

The specific bi-modal distribution of OTX2 binding around the TSSs, as we investigated in medulloblastoma, strongly differs from the binding patterns of MYC and other transcription factors like
GATA1 and TCF4 [26,27,36–38]. This bi-modal OTX2 pattern was observed both in cells with endogenous OTX2 expression (D425) as well as in cells with induced transgene expression (MED8A and DAOY).

The bi-modal distribution consists both of promoter regions with single and multiple OTX2-binding peaks. The class of promoter regions with both multiple OTX2-binding peaks with MYC binding differed from the other classes, as they were associated with higher gene expression in D425 medulloblastoma cells and in primary medulloblastoma tumors. Moreover, genes within this class of promoter regions were enriched for stem cell and medulloblastoma specific gene expression. Thus, OTX2 seems to have a functional interaction with MYC, which might explain why both genes are frequently co-expressed at high levels in medulloblastoma [5,6,22].

Even though the binding pattern might be specific for OTX2, other binding properties were consistent with those found for MYC in D425 cells or from what has been described for other transcription factors [26,27,36–38]. Similar to genes as MYC or OCT4, OTX2 binds to a large number of genes [26,39]. This frequent binding does not always result in gene regulation, as usually only for around a third or less of the bound genes the expression levels change after overexpressing or silencing the transcription factor [40]. We obtained similar results in OTX2 silencing and ectopic overexpression experiments [8,9].

The relation between transcription factors binding to promoter regions and gene expression can be biased by the methods used to...
determine both binding and regulation. First of all, to assign bound regions to the nearest known genes might be inadequate. It disregards many other forms of gene regulation by, for instance, enhancers, which can be located far away from a gene [40]. Secondly, silencing of a transcription factor is commonly used to identify its target genes. The transcription factor levels are greatly

Figure 5. OTX2-binding motifs do not correlate with gene expression levels. All OTX2-binding peaks were sorted by the expression in D425 cells of the associated genes and binned per 400. The motif frequency for each bin is displayed as a function of average expression. For all three OTX2-binding motifs, there is no relation between gene expression levels and motif occurrence within the peaks. doi:10.1371/journal.pone.0026058.g005

Figure 6. Multiple OTX2-binding peaks with MYC binding is associated with high gene expression. A and B. OTX2-bound promoter regions are classified by single or multiple OTX2-binding peaks with or without additional MYC-binding. For each of these promoter classes the percentage of bound promoter regions was calculated in different expression categories using either expression data from D425 cells (A) or expression data from 10 primary medulloblastoma tumors that have both OTX2 and MYC expression (B). Promoter regions with multiple OTX2-binding peaks and MYC binding were clearly enriched among the gene categories that show higher gene expression both in D425 cells and in tumors. C. Genes within the promoter class with multiple OTX2-binding peaks and MYC binding showed significantly higher expression levels in D425 cells, primary medulloblastoma tumors and human neural embryonic stem cells as compared to genes in other classes (minimal p<1.00E-7, T-test). This difference was not observed using expression data of normal cerebellum. doi:10.1371/journal.pone.0026058.g006
OTX2 and MYC Binding Links to High Gene Expression

The binding characteristics of OTX2 raise the question, whether OTX2 only has classical transcription factor function. For other highly expressed transcription factors with frequent binding, like MYC, additional epigenetic functions have been described. Peng et al. suggested that OTX2, like CRX, might recruit HAT-containing co-activators such as CBP, P300, and GCN5 via direct interaction with ATXN7 to promote histone acetylation [42,43]. Unfortunately direct evidence was not shown. However, for the homologue ATXN1 interaction was shown in a yeast2hybrid experiment [44]. ATXN7 is highly expressed in medulloblastoma tumors and cell lines. OTX2 may function in a similar way in promoting epigenetic changes. With this concept in mind, the similarities between the bi-modal distribution of OTX2 and those of histone modifications such as H3K4me3 and H3K9Ac, both marks for active gene expression, could hint to a direct role of OTX2 in histone modification [45,46].

Materials and Methods

**ChiP-on-chip**

D425 medulloblastoma cells were cultured in MEM medium (Invitrogen, Carlsbad, CA), supplemented with 10% fetal bovine serum, 0.1 mM MEM non essential amino acids, 200 mM glutamine, 100 U/mL penicillin and 100 μg/mL streptomycin (Invitrogen) at 37°C in a humidified atmosphere containing 5% CO2. Two days after plating, cells were cross-linked with 1% formaldehyde for 10’. After washing, cells were incubated for 5’ in swelling buffer (5 mM PIPES, 85 mM KCl, 0.5% SDS) and passed through a 23G needle. Isolated nuclei were lysed for 10 – 15 second in 1% TritonX-100/150 mM NaCl/50 mM Tris-HCl/2 mM EDTA and cleared for 30’ with 40 μL protein A agarose (Roche) and incubating for 30’ at 4°C. DNA was purified using DNA extraction kit (Qiagen, Cambridge, MA) with 40 μL beads were added to cleared samples and incubated for 30’ at 3°C. The next day beads were sequentially washed with 0.1% SDS/1% Triton-X-100/150 mM NaCl/20 mM Tris-HCl/2 mM EDTA, with the same solution with 500 mM NaCl, with 1% Deoxycholate, 1% NP40/250 mM LiCl/10 mM Tris-HCl/2 mM EDTA and finally with 10 mM Tris-HCl/10 mM EDTA. DNA was eluted in 500 μL 100 mM NaHCO3/1% SDS. 20 μL 5 M NaCl was added before digesting at 65°C for 4 h. Next 10 μL 0.5 M EDTA, 20 μL 1 M Tris-HCl pH 6.5 and 2 μL 10 mg/mL Proteinase K (Roche) were added and incubated at 37°C for 1 h to degrade protein. DNA was degraded by adding 5 μL 10 mg/mL RNase A (Roche) and incubating for 30’ at 37°C. DNA was purified using Qiagen PCR purification kit (Qiagen, Germantown DE) and quantified with Quant-IT Picogreen (Invitrogen).

The recovered DNA was amplified for labeling as described previously [28]. Labeling of the material, hybridization to the 2.1 M Deluxe Promoter Array, scanning of the arrays and peak calling were performed by Nimblegen, Inc. The ChiP-on-chip experiments with OTX2 in D425, MED8A and DAOY cells were previously published [6,9].

**Data analyses**

All data were scaled as 2log signal ratios by the Nimblegen algorithm (Nimblegen) and mapped to transcription start sites (TSSs) in the genome. If a gene has multiple promoter regions, TSSs with less than 150 bp spacing from the previous were discarded. All remaining promoter regions were aligned and the average 2log binding signal was calculated over 50 bp bins relative...
to the TSS. OTX2-binding peaks were called significant by the manufacturer’s algorithm. Graphs of the average \(\log_2\) signals and the percentage of peaks as a function of the distance to the TSS were generated in R2 [http://r2.aml.nl]. Heatmaps of signals for an individual promoter region were generated in TMEV [47]. Only data of promoter regions with more than 100 bins with informative data within ~5000 bp to 3000 bp were included. The promoter regions were sorted based on the expression of the corresponding gene in D425 cells (GSE22875) [8].

Promoter regions harboring at least one binding peak with its center overlapping the region of ~2000 to 2000 bp surrounding the TSS, were defined as bound by OTX2 or MYC. Distance between OTX2- and MYC-binding peak centers were calculated for all single OTX2-bound promoter regions. The expected distance between OTX2- and MYC-binding peak centers was generated by randomizing all OTX2-binding peak locations in regards to the TSS locations in Excel and taking the average over 3 randomizations. The percentage of OTX2-binding peaks within different distance ranges was plotted for the calculated and expected values. A Fisher’s exact test was used for determining significant changes.

All promoter regions were classified based on the combination of OTX2 and MYC binding within the ~2000 bp and 2000 bp region. The average expression of genes within these classes was calculated using data of D425 cells (GSE22875), 10 primary non-WNT/non-SHH medulloblastoma with both high OTX2 and MYC expression (GSE10327 and GSE12992), 9 normal cerebellum samples (GSE3526) and undifferentiated human embryonal cells (GSE9921). Gene set enrichment analyses were performed using the DAVID tool [http://david.abcc.ncifcrf.gov/] and BROAD tool [http://www.broadinstitute.org/gsea] [31–33].

**References**


