

Data mining of pediatric medulloblastoma microarray expression reveals a novel potential subdivision of the Group 4 molecular subgroup

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Abstract. Medulloblastoma is the most common type of solid brain tumor in children. This type of embryonic tumor is highly heterogeneous and has been classified into 4 molecular subgroups based on their gene expression profiles: WNT, SHH, Group 3 (G3) and Group 4 (G4). WNT and SHH tumors exhibit the specific dysregulation of genes and pathways, whereas G3 and G4 tumors, two of the more frequent subtypes, are the least characterized. Thus, novel markers to aid in the diagnosis, prognosis and management of medulloblastoma are required. In the present study, microarray gene expression data was downloaded from the Gene Expression Omnibus database, including data from the 4 subgroups of medulloblastoma and healthy cerebellum tissue (CT). The data was utilized in an *in silico* analysis to characterize each subgroup at a transcriptomic level. Using Partek Genomics Suite software, the data were visualized via hierarchical clustering and principal component analysis. The differentially expressed genes were uploaded to the MetaCore portal to perform enrichment analysis using CT gene expression as baseline, with fold change thresholds of <-5 and >5 for differential expression. The data mining analysis of microarray gene expression data enabled the identification of a range of dysregulated molecules associated with each subgroup of medulloblastoma. G4 is the most heterogeneous subgroup, as no definitive pathway defines its pathogenesis; analysis of the gene expression profiles were associated with the G4 α and G4 β subcategories. TOX high mobility group box family member 3, synuclein α interacting protein and, potassium voltage-gated channel interacting protein 4 were identified as three novel potential markers for

distinguishing the α and β subcategories of G4. These genes may be associated with medulloblastoma pathogenesis, and thus may provide a basis for researching novel targeted treatment strategies for G4 medulloblastoma.

Introduction

Tumors of the central nervous system (CNS) are the most frequent type of solid tumor identified in children. Among them, medulloblastoma has the highest incidence rate, at 6 per 1,000,000 in children aged 1-9 years in the United States (1), which is 10-fold greater than the incidence rate in adults (2). Since the organogenesis of the cerebellum is strongly associated with its susceptibility to oncogenic transformation, medulloblastomas are classified as embryonic tumors, which is consistent with the high incidence rate of tumors derived from this organ in children (3,4). Conventionally, the histological classification of medulloblastoma has been established to comprise the following variants: Classic, desmoplastic/nodular, anaplastic, large-cell and medulloblastoma with extensive nodularity (5). Current treatment options include surgery, radiotherapy and chemotherapy, and treatment is selected based on patient age, among other risk factors (6). These strategies typically achieve a 5-year survival rate of 50-80%; however, severe neurological secondary effects can result from such treatments (6-8).

The discovery of the molecular landscape of medulloblastoma has provided a new perspective in the research of the disease. This has allowed the elucidation of the origin of medulloblastoma, and how specific molecular dysregulation can affect the treatment response and subsequent clinical outcomes. The molecular classification of medulloblastoma is based on 4 subgroups: WNT, SHH, Group 3 (G3) and Group 4 (G4). The WNT subgroup is associated with the dysregulation of Wnt signaling; it accounts for 10% of all medulloblastoma cases and is associated with the most positive prognosis (9,10). This subgroup is characterized by mutations in catenin β 1, *APC* and *Frizzled*, among other genes, which are known to maintain and activate pathways involving the β -catenin protein, a transcription factor upregulating cell proliferation, survival and migration (11). Additionally, the WNT subgroup is associated with a predisposition to the

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development of Turcot syndrome, and may also be associated with deletions in chromosome 6 (12-14). The SHH subgroup is characterized by the dysregulation of the sonic hedgehog pathway. It accounts for ~30% of all medulloblastomas, and is associated with an intermediate prognosis (9,10). SHH medulloblastomas are also associated with Gorlin syndrome (15,16). SHH medulloblastomas principally exhibit the inactivation of patched 1 and suppressor of fused homolog, missense mutations in smoothed (SMO), and amplifications of GLI family zinc finger 2. These genetic alterations promote the translocation of the transcription factor, GLI, into the nucleus, which can lead to the activation of cancer driver genes (17). WNT and SHH are the best characterized subgroups of medulloblastoma, which may enable specific therapeutic targeting.

Group 3 (G3) represents ~25% of medulloblastoma cases, and is characterized by amplifications in *MYCN* and orthodenticle homeobox 2 (*OTX2*), the gain of chromosomes 7 and 17q, and the loss of chromosomes 10q or 16q (9). Group 4 (G4) is the most common subgroup, accounting for ~35% of all cases (9,10); it is biologically heterogeneous and difficult to characterize due to its molecular markers being shared with G3 and SHH. These markers include mutations in lysine demethylase, and amplifications of *OTX2* or lysine methyltransferase 2D, among others. G3 and G4 are associated with a relatively poor prognosis compared with the WNT and SHH subgroups (9).

The high heterogeneity and prevalence of G3 and G4 medulloblastomas highlight the requirement to establish molecular classifications for each subgroup based on specific markers detectable by inexpensive techniques. Ellison *et al* (18) reported an immunohistochemical method for distinguishing between SHH/WNT and non-SHH/WNT tumors. This method considers specific markers of each subgroup, including GRB2 associated binding protein 1, β -catenin, filamin A and Yes associated protein 1. However, it cannot differentiate between the G3 and G4 subgroups. The identification of novel biomarkers would increase the efficiency of molecular diagnosis, and may be achieved through the identification and characterization of the key pathways that are distinctly dysregulated in the G3 or G4 subgroups.

In the present study, an *in silico* analysis of the 4 molecular subgroups of medulloblastoma was performed with the aim of characterizing potential novel markers for the identification of each subgroup, with an emphasis on the characterization of G4. A number of key markers were identified, allowing the classification of further subdivisions within G4. This data may contribute to the more effective classification of medulloblastoma, and aid in the identification of alternative therapeutic targets, particularly for G4 medulloblastoma.

Materials and methods

Datasets. Affymetrix microarray U133_Plus 2 Array data was downloaded from the Gene Expression Omnibus database (<http://www.ncbi.nlm.nih.gov/geo>). This included medulloblastoma and healthy control cerebellar tissue (CT) data. The microarray data included various characteristics, including the sample information (tissue type and disease status), RNA purification method, RNA quality, RNA integrity, RNA concentration and the microarray protocol used. Tumor

expression profiles were grouped according to the medulloblastoma molecular subgroups. The following datasets were included in the present study: GSE4036, GSE10327 (19-21), GSE37418 (20-22), GSE44971 (23) and GSE49243 (20,24).

Data analysis. Bioinformatics analysis was performed using the Partek Genomics Suite version 6.6 (Partek, Inc., St Louis, Missouri, USA). In brief, all datasets were uploaded to the Partek Genomics Suite and summarization was performed with Median Polish analysis with quantile normalization and background correction using a robust multiarray average. The probe set was then transformed to \log_2 . A second selection of the microarray dataset was performed based on an analysis by Quality Control Microarray processing according to a previous study (25). In the aforementioned analysis the fluorescence intensity of the microarray quality control was evaluated using bioB, bioC, bioD and Cre, at final concentrations of 1.5, 5, 25 and 100 pM, respectively. Additionally, Poly-A RNA controls were evaluated using Dap, Thr, Phe and Lys to final concentrations of 1:7,500, 1:25,000, 1:50,000 and 1:100,000, respectively. Microarrays without the relative signal intensities of Poly-A RNA and hybridization controls were excluded from the present study.

Differentially expressed genes were determined using the data from healthy CT to define baseline expression. The geometric least squares means model was used for the following independent analyses: WNT vs. CT; SHH vs. CT; G3 vs. CT; and G4 vs. CT. Differential gene expression was also detected between G3 and G4 using G3 as the baseline, between the subsequently defined subgroups G4 α and G4 β using G4 β as the baseline, and between WNT, SHH, G3, G4 α and G4 β , using CT as the baseline. Significantly differentially expressed genes were detected by an analysis of variance using a false discovery rate threshold of <0.005 and fold change (FC) thresholds of <-5 and >5. Hierarchical clustering heatmaps were constructed using the Euclidean distance method.

Systems biology. The differentially expressed genes were uploaded to the MetaCore portal (Thomson Reuters, New York City, NY, USA) for enrichment analysis, in which FC was used as the parameter for differential expression. Significant signaling pathways were selected using a Z-score, as outlined in our previous study (26).

Results

Medulloblastoma expression profiles can be grouped based on the molecular subgroups. Initially, the data from 237 microarray expression profiles of medulloblastoma tumor and CT samples were downloaded. All microarrays were subjected to quality control analysis; ~42% of all arrays were excluded based on the Poly-A RNA controls. The signal intensity demonstrated a high level of variation, as previously reported (25,27).

A total of 137 expression profiles were included in the analysis, including profiles from the following molecular subgroups: WNT, n=17; SHH, n=27; G3, n=20; G4, n=53 and healthy CT, n=20 (Table I). The medulloblastoma samples were successfully grouped based on their molecular classification using the CT group as a reference control (Fig. 1).

Table I. DEGs in molecular subgroups compared with the control cerebellar tissues (n=20).

Subgroup name	Samples, n	DEGs, n		
		Upregulated	Downregulated	Total
WNT	17	1,073	1,092	2,165
SHH	27	728	991	1,719
G3	20	673	1,117	1,790
G4	53	602	801	1,403

DEG, differentially expressed genes; G3, group 3 medulloblastoma; G4, group 4 medulloblastoma.

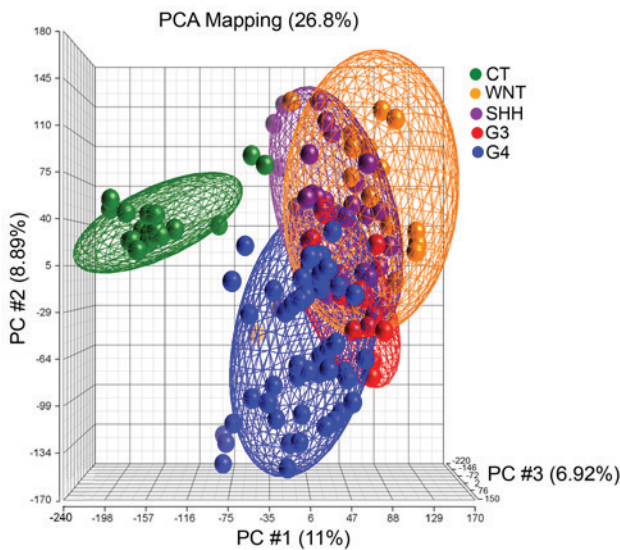


Figure 1. Gene expression patterns in medulloblastoma subgroups. PCA was performed with an expectation-maximization algorithm in Partek Genomics Suite v6.6. The PCA depicts the overlapping of gene expression between the 4 molecular subgroups: WNT, orange; SHH, purple; G3, red; G4, blue; and CT, green. PCA, principal component analysis; CT, control cerebellar tissue.

Gene expression profiling revealed potential targets for molecular subgroup classification. The expression profiles of the medulloblastoma molecular subgroups compared with healthy CT revealed numerous differences. The number of upregulated or downregulated differentially expressed genes were as follows: WNT, n=2,165; SHH, n=1,719; G3, n=1,790; and G4, n=1,403 (Fig. 2; Table I). The transcripts overexpressed in the WNT subgroup included frizzled class receptor 10 (FC, 55.2), Dickkopf WNT signaling pathway inhibitor 1 (FC, 16.6), forkhead box D1 (FC, 10.6), ALK receptor tyrosine kinase (FC, 6.4) and forkhead box L2 (FC, 6.3; Fig. 3A). Claudin 1 (FC, 12.33), ADAM metalloproteinase with thrombospondin type 1 motif 6 (FC, 11.43) and growth arrest specific 1 (FC, 8.19) were upregulated in the SHH subgroup (Fig. 3B); FEZ family zinc finger 2 (FC, 6.83), ADP Ribosylation Factor Like GTPase 4D (FC, 6.41) and sperm associated antigen 5 (FC, 5.25) (Fig. 3C) were upregulated in G3; G4 exhibited the overexpression of caspase recruitment domain family member 10 (FC, 10.23), CXXC finger protein 4 (FC, 6.64), SH2 domain

containing adaptor protein B (FC, 5.92) and CXC motif chemokine ligand 14 (FC, 5.38; Fig. 3D).

Differential gene expression between G3 and G4 reveals a novel subgroup in G4. The molecular classification of medulloblastoma and other types of CNS tumor was previously investigated (28). Defining the expression profiles associated with G3 and G4 has been a particular challenge in medulloblastoma research, as the groups share several molecular characteristics and are considered the most internally heterogeneous (29). In order to identify potential molecular markers associated with G3 and G4, G3 was used for a comparative analysis against G4. The analysis identified 224 differentially expressed genes; 142 were upregulated and 82 were downregulated in G4 compared with G3 (Fig. 4). The differentially expressed genes allowed clustering into 2 distinct groups, representing G3 and G4, as illustrated by the heatmap. However, the G4 cluster unexpectedly demonstrated 2 profiles, with a small secondary cluster representing 12 samples (~25%; Fig. 4).

The results indicated a potential sub-classification of G4. In order to identify the molecular differences within G4, G4 samples were sub-classified as G4 α and G4 β [36 (75%) and 12 samples (25%), respectively; (Fig. 5)]. A comparative analysis was performed using G4 β as the baseline against G4 α . The analysis identified a differential expression profile for G4 α , with 3 genes upregulated and 33 downregulated (Table II). The 5 molecular subgroups of medulloblastoma were integrated for a comparative analysis using the CT profile as the baseline against WNT, SHH, G3, G4 α , and G4 β . The WNT, SHH, and G3 subgroups retained the same molecular profiles as the first analysis of only 4 subgroups, whereas the G4 α and G4 β subgroups demonstrated 1,418 and 1,320 differentially expressed genes, respectively (Fig. 6). However, a number of molecules shared expression patterns among the molecular subgroups, including G4 α and G4 β , which would be expected, as molecular similarities between medulloblastoma tumors of all types are inevitable (Table III).

Enrichment analysis demonstrated potential therapeutic targets associated with medulloblastoma subgroups. Enrichment analysis enabled the identification of gene profiles and pathways shared between each molecular subtype of medulloblastoma (Fig. 7). The most common medulloblastoma-associated process was ‘cell cycle’, associated with the upregulation of kinesin family member 11, cell division cycle 20, mitotic arrest deficient 2 like 1, kinetochore complex component and cyclin B1 (Fig. 7A). The ‘renin-angiotensin pathway’ was significantly downregulated, which was associated with the downregulated expression of angiotensinogen and angiotensins I, II, III, IV, -(2-10), -(1-7) and -(1-9) (Fig. 7B). However, differences in the level of expression existed between the subgroups, consistent with the subclassifications described in the present study (Fig. 7A and B).

Discussion

This data mining analysis of microarray gene expression data enabled the identification of a range of dysregulated molecules associated with each subgroup of medulloblastoma, as has

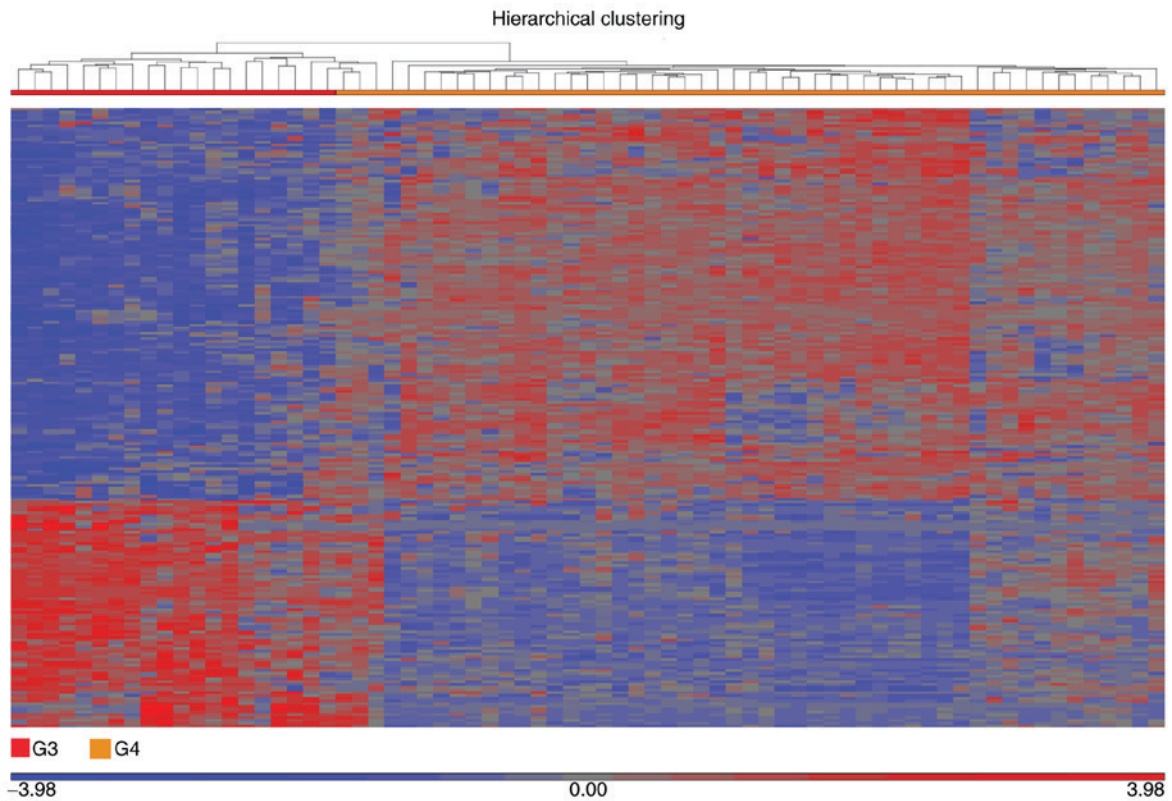


Figure 4. Hierarchical clustering of the molecular subgroups G3 and G4. The heatmap depicts the differentially expressed genes in G3 compared with G4, as evaluated by analysis of variance using the geometric least squares means model, with G3 as the baseline. Differential expression was indicated when the fold change was >5 or <-5 and the false discovery rate was <0.005 . Clustering analysis identified two subgroups within G4 based on the dissimilarity of samples as assessed using a Euclidean model by means of average linkage, which represented 48 tumors in total. A total of 12 G4 samples exhibited significantly different gene expression profiles compared with the remaining 36. G3, group 3 medulloblastoma; G4, group 4 medulloblastoma.

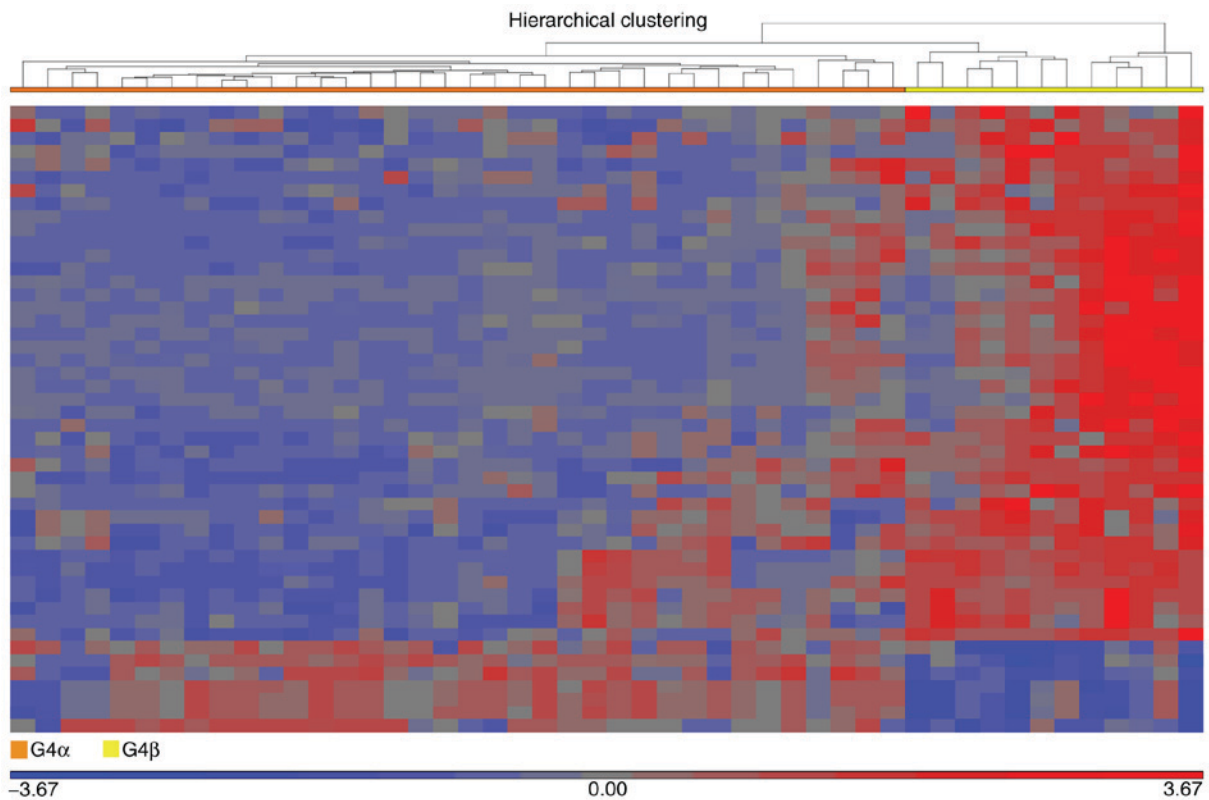


Figure 5. Fractionation of G4 medulloblastoma. The heatmap illustrates 48 dysregulated genes in G4 medulloblastoma. The dissimilarity of samples based on average linkage indicated the fractionation of G4 into the potential subgroupings of G4 α (left; orange bar) and G4 β (right; yellow bar). Differential expression values were included when the fold change was >5 or <-5 and the false discovery rate was <0.005 . G3, group 3 medulloblastoma; G4, group 4 medulloblastoma.

Table II. Differentially expressed genes in the G4 α subgroup compared with the G4 β subgroup.

Gene symbol	Gene name	Fold change (G4 α vs. G4 β)
TOX3	TOX high mobility group box family member 3	8.61506
SNCAIP	Synuclein α interacting protein	6.85187
KCNIP4	Potassium voltage-gated channel interacting protein 4	6.27879
PLXDC1	Plexin domain containing 1	-3.02931
BCL11B	B-cell CLL/Lymphoma 11B	-3.06849
ABCA4	ATP-binding cassette sub-family A member 4	-3.07119
GALNT10	Polypeptide N-acetylgalactosaminyltransferase 10	-3.13204
GLCCI1	Glucocorticoid induced transcript 1	-3.22556
FAM126A	Family with sequence similarity 126, member A	-3.24904
SLC1A7	Solute carrier family 1, member 7	-3.29459
GALNT14	Polypeptide N-acetylgalactosaminyltransferase 14	-3.33326
IGSF11	Immunoglobulin superfamily, member 11	-3.33354
SHROOM2	Shroom family member 2	-3.39392
CNTN3	Contactin 3	-3.83419
GNGT2	G protein subunit γ transducin 2	-3.85892
AIPL1	Aryl hydrocarbon receptor interacting protein-like 1	-3.99598
RASGRF2	Ras protein-specific guanine nucleotide-releasing factor 2	-4.01560
RP1	Retinitis pigmentosa 1	-4.04201
NR2E3	Nuclear receptor subfamily 2, group E, member 3	-4.36478
CRX	Cone-rod homeobox	-4.41841
LAPTM4B	Lysosomal protein transmembrane 4 β	-4.56260
PTPN13	Protein tyrosine phosphatase, non-receptor type 13	-4.76854
PDC	Phosducin	-4.80708
RCVRN	Recoverin	-4.91791
ANO2	Anoctamin 2	-5.11475
MPP4	Membrane protein, palmitoylated 4	-5.39617
RD3	Retinal degeneration 3	-5.39937
FAM19A4	Family with sequence similarity 19, member A4, C-C motif chemokine-like	-5.76661
CDHR1	Cadherin-related family member 1	-5.80075
CABP5	Calcium binding protein 5	-7.79064
ZNF385B	Zinc finger protein 385B	-8.85360
IMPG2	Interphotoreceptor matrix proteoglycan 2	-9.61426
PRSS12	Protease, serine 12	-9.84918
SST	Somatostatin	-9.92109
NRL	Neural retina leucine zipper	-10.53520
PDE6H	Phosphodiesterase 6H	-11.56650

G4, group 4 medulloblastoma.

been previously achieved (9,28). Furthermore, a potential subcategorization of G4 was defined. G4 medulloblastoma is the most frequently occurring molecular subgroup, as well as one of the most heterogeneous, as no definitive pathway defines its pathogenesis.

Despite the classification of medulloblastoma into 4 subgroups, the heterogeneity of G3 and G4 and their association with poorer prognoses remain unaddressed. Thompson *et al* (30) described 5 subgroups instead of the standard 4, suggesting some overlap between the G3 and G4

subgroups and/or a subdivision of G4 itself. Additionally, Cho *et al* (31) reported an analysis of the mRNA transcriptome via a high-density single-nucleotide polymorphism array and miRNA analysis, in which 6 molecular subgroups were identified; the WNT and SHH subgroups remained the same, whereas G3 was subclassified into the C1/C5 subgroups and G4 into the C2/C4 subgroups, reflecting the lack of homogeneity in the G3 and G4 subgroups. These C2 and C4 G4 subcategories may be equivalent to those described in the present study.

Table III. Potential therapeutic targets in medulloblastoma tumors, including the top ten upregulated and downregulated differentially expressed genes in the 5 subgroups of medulloblastoma.

Gene symbol	Fold change vs. control cerebellar tissue				
	WNT	SHH	G3	G4α	G4β
SOX11	50.4508	159.2550	114.7920	214.6350	157.7430
LHX2	19.0600	18.1300	62.1164	118.7020	45.9915
KIAA0101	89.8103	97.5187	119.3500	106.7370	70.2860
TOP2A	97.4276	74.4959	95.3006	89.4034	56.8238
TMSB15A/B	27.3665	131.5370	36.4977	80.2035	74.1441
DACH1	25.9512	23.0074	28.4259	74.5587	41.3941
SOX4	13.2496	15.9908	25.3652	64.0049	53.1116
DACH1	19.2667	14.5598	16.1719	61.2870	21.7303
RRM2	48.8038	47.4022	75.8280	55.5282	46.5205
IGFBPL1	68.8801	60.7771	10.3575	50.0114	48.5435
ITPR1	-26.0343	-27.0244	-78.6472	-58.7188	-47.0085
SYT1	-8.2123	-8.1780	-25.8050	-62.9443	-37.5653
SPHKAP	-98.0768	-21.4717	-91.2947	-64.4953	-42.0679
PDE1A	-119.2340	-13.2837	-128.5230	-66.5903	-25.8941
CDR1	-78.4458	-66.2995	-75.0443	-83.1560	-78.4922
CBLN3	-82.5110	-97.7424	-131.9180	-97.2893	-71.7417
CRTAM	-142.5620	-119.6880	-176.9190	-98.6054	-91.3960
CALB1	-90.1248	-100.8540	-50.7010	-121.3370	-113.9070
PVALB	-125.1260	-90.7036	-243.5880	-175.7630	-113.7100
GABRA6	-254.6810	-245.7720	-171.3970	-192.7920	-133.8460

G3, group 3 medulloblastoma; G4, group 4 medulloblastoma.

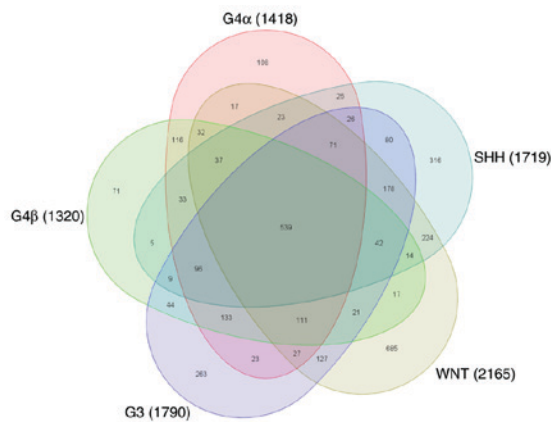


Figure 6. Gene expression profiles associated with the molecular subgroups of medulloblastoma. The Venn diagram represents the 5 subgroups of medulloblastoma. A total of 539 dysregulated genes were common between the 5 subgroups. Distinct differentially expressed genes was identified for WNT (n=685), SHH (n=316), G3 (n=263), G4α (n=108) and G4β (n=71). G3, group 3 medulloblastoma; G4, group 4 medulloblastoma.

It has been indicated that G3 and G4 medulloblastoma express gene members of pathways associated with photo-reception and neuronal function, thus suggesting a grade of differentiation (32). In the present study, the overexpression of TOX high mobility group box family member 3 (*TOX3*), potassium voltage-gated channel interacting protein 4 (*KCNIP4*),

and synuclein α interacting protein (*SNCAIP*) was identified in the G4 α group compared with G4 β . *TOX3* is important in the development of the CNS (33) and its expression is correlated with neuronal markers, including Nestin and SOX2. The TOX3 protein participates in the regulation of DNA structure and coiling, and thus aids in transcriptional regulation. For instance, TOX3 interacts with the CAMP Responsive Element Binding Protein (CREB)/CREB binding protein complex and regulates the transcription of genes dependent on calcium ions, and is associated with neuronal survival (34). In addition, *TOX3* is expressed in breast and lung cancer (35).

The overexpression of *KCNIP4* was identified in the G4 α subgroup only. The *KCNIP* family comprises a group of small calcium-binding proteins. *KCNIP4* encodes a potassium ion transporter directly associated with neuronal function, which interacts with presenilin, a protein associated with early-onset familial Alzheimer's disease (36). To date, *KCNA1* (10) and *KCNJ2* (37) have been reported as potential markers of G4 medulloblastoma; however, to the best of our knowledge, this is the first time that *KCNIP4* has been identified as specifically associated with the G4 α subgroup of medulloblastoma.

SNCAIP has been described by Northcott *et al* (37) as a key gene in the subcategorization of G4 medulloblastoma, which is supported by the results of the present study. Northcott *et al* (37), reported that a tandem duplication of *SNCAIP* defined a novel subtype of G4 medulloblastoma, 4 α , which comprised 10.4% of G4 medulloblastoma cases among

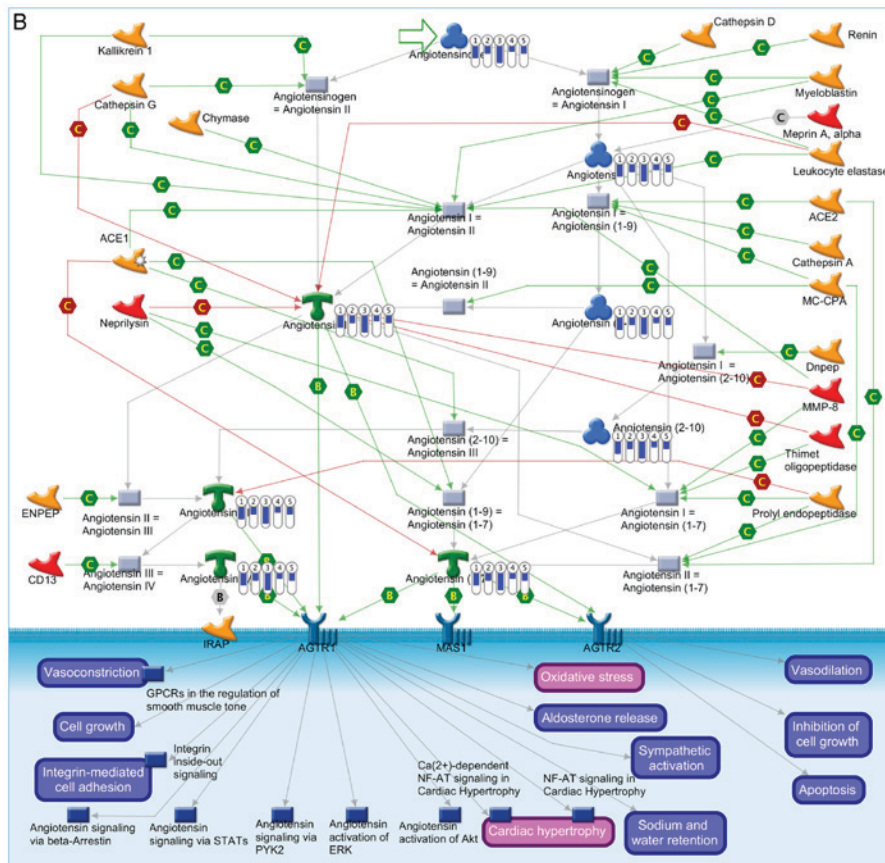
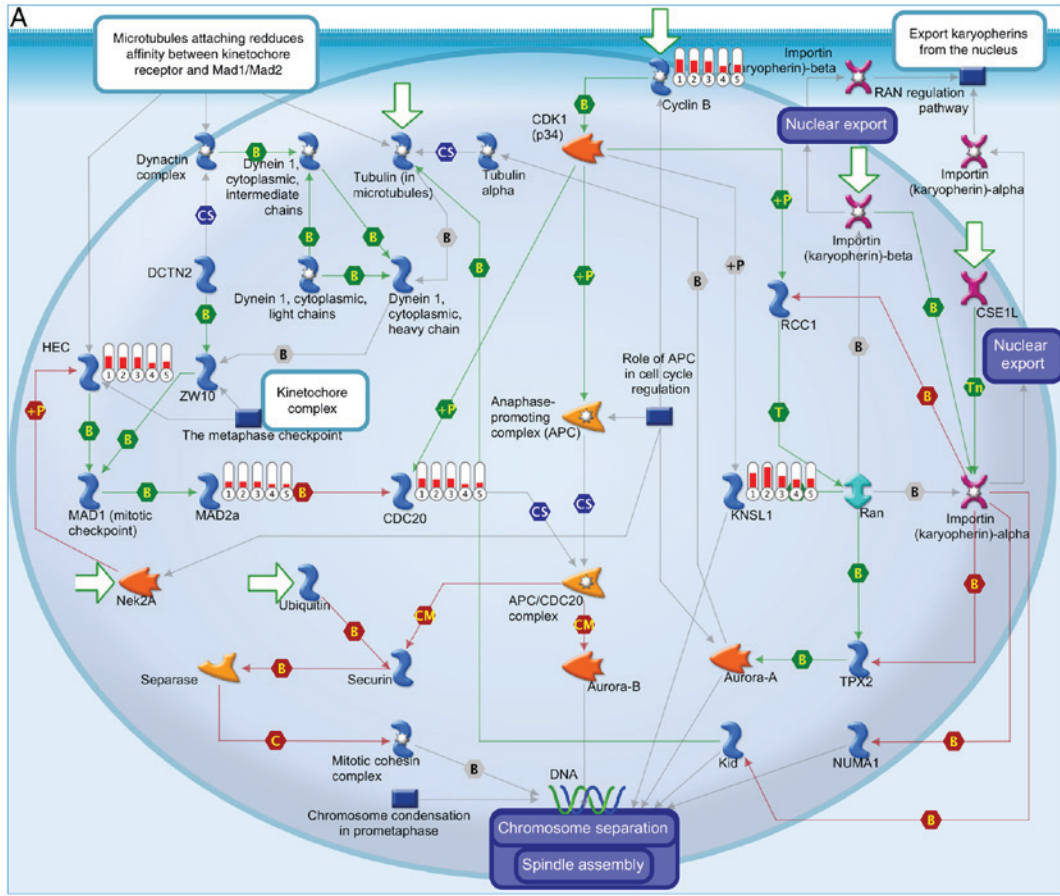


Figure 7. Enrichment analysis of the differentially expressed genes in the 5 subgroups of medulloblastoma. The thermometers indicate expression (red, upregulated; blue, downregulated). The numbers in the thermometers indicate the molecular subgroups (1, WNT; 2, SHH; 3, group 3; 4, group 4a and 5, group 4b medulloblastoma). (A) Canonical pathways of the upregulated differentially expressed genes in the 5 molecular subgroups of medulloblastoma. (B) Canonical pathways of the downregulated differentially expressed genes in the 5 molecular subgroups of medulloblastoma.

1,087 medulloblastoma genomes. The *SNCAIP* duplication was associated with a 1.5-fold increase in *SNCAIP* expression in G4 α compared with G4 β . Significantly, *SNCAIP* duplications are mutually exclusive with *MYCN* and *CDK6* amplifications (37). It has been established that synphilin-1 in neurons interacts with α -synuclein, a protein present in Lewy bodies in patients with Parkinson's disease (38).

Northcott *et al* (37) also reported that somatic copy number aberrations (SCNAs) were common in medulloblastoma and were enriched depending on the subgroup. Specific SCNAs were associated with TGF- β in G3, and NF- κ B in G4, which may enable the identification of novel targets for the specific treatment of different subgroups of medulloblastoma. Despite the existing specific therapies for SHH medulloblastoma, including GDC-0449, an inhibitor of the SHH pathway that targets the SMO receptor (39), it is necessary to identify alternative therapies for all the molecular subgroups, particularly for those associated with a relatively poor prognosis, including G3 and G4. The markers identified in the present study, together with other markers reported elsewhere, may form the basis for new approaches to treat medulloblastoma.

Further studies are required to verify the potential of the markers identified in the present study to define G4 subcategories. It will be important to validate the presence of these markers in patient samples, and explore whether they are associated with a relatively poor prognosis in medulloblastoma, as well as how they participate in the physiopathology of the disease.

In conclusion, three novel potential markers to differentiate G4 medulloblastoma into two subclassifications, *TOX3*, *KCNIP4* and *SNCAIP*, have been identified in the present study. This may provide a basis for future studies on the characterization of G4 medulloblastomas. Future research should focus on these genes as potential biomarkers, in the pathogenesis of medulloblastoma, and as targets for the development of targeted therapies.

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Availability of data and materials

The datasets analyzed during the current study are public and available in the Gene Expression Omnibus database, www.ncbi.nlm.nih.gov/geo (accession nos. GSE4036, GSE10327, GSE37418, GSE44971 and GSE49243).

Authors' contributions

RACR and SJM conceived and designed the work. RACR, SJM, and VMDB acquired, analyzed, and interpreted the data.

All authors discussed and wrote the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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