■ 特集 ビジュアル小児外科疾患のフォローアップ・プログラム―手術直後から遠隔期の問題点まで

リンパ管腫

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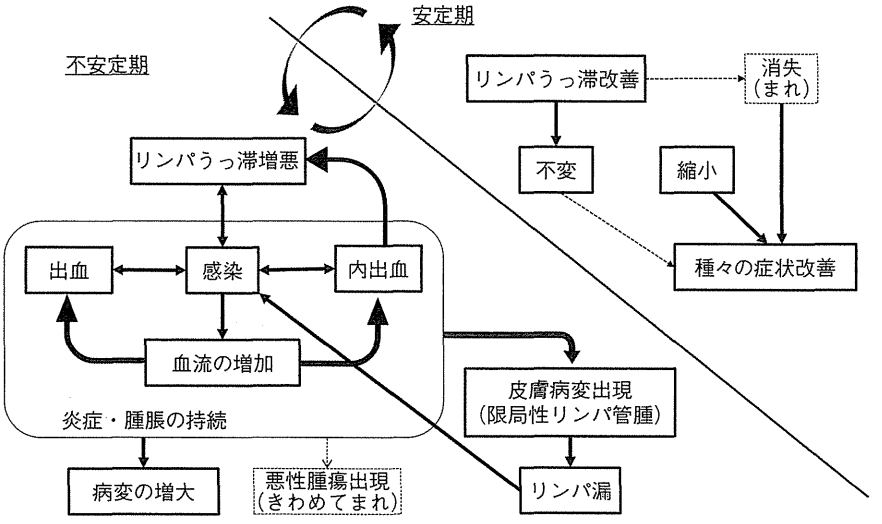

図 1 リンパ管腫の長期経過

リンパ管腫病変は，長期経過中に安定してあまり問題を起こさない場合と，炎症を中心として急性の問題を繰り返す場合がある。多くの場合，一定の治療ののちに症状は安定し，腫瘤内のリンパ液貯留も減少し，さまざまな症状も不変もしくは改善傾向を示す。一部に炎症を繰り返す場合には腫脹も徐々に増大し，血流も増加して悪循環に陥る。

はじめに

リンパ管腫は主に小児期に発症する腫瘤性病変で，正常組織内に網目状に広がる大小さまざまなリンパ嚢胞からなる疾患であり，小児外科領域ではよく知られている。その生物学的には腫瘍的特徴があまりみられないことより，近年 International Society for the Study of Vascular Anomalies (ISSVA) の疾患分類 (http://issva.clubexpress.com/docs.ashx?id=178348) に沿って世界的に名称が lymphangioma から (cystic or common) lymphatic malformation へと移行しつつあり，わが国でも「リンパ管奇形」とよばれることが徐々に多くなっている。

本疾患の治療の柱は硬化療法と外科的切除である。多くのリンパ管腫患者にこれらの治療は有効であり，満足のいく結果が得られる。しかし，逆

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に約20%はなんらかの問題をかかえる難治性と考えられており，現行の治療では十分な治療効果が得られない。そういう病変をもった患者は，長期にわたり病気とつきあうことを余儀なくされている[1]。

本稿では，とくに外科的切除後の問題と管理法，および術後遠隔期に生じてくる問題点に焦点をあてて論ずる。

Ⅰ．外科的切除の選択

リンパ管腫は，サイズや部位により重症度に非常に大きな幅があるが，治療法の選択肢は限られている。外科的切除，硬化療法のコンビネーションが主体である。主に内部の性状（嚢胞状，海綿状），病変の部位（気道，血管，神経との関係），年齢などにより選択する。

容易に切除ができる場合，海綿状タイプ（microcystic）である場合，または急速な腫脹により気道閉塞や消化管閉塞などの重篤な機能不全を生じる可能性がある場合以外は，硬化療法をまず選択することが多い。繰り返しも可能であるが，硬化療法の効果には限界があり，次のステップとして外科的切除が選択される。

悪性ではない本疾患に対しては，外科的切除にはバランス感覚が必要で，決して「完全切除」のために過度に健常組織と機能を犠牲にしてはならない[2,3]。あくまで病変による種々の「症状を改善」することを目的の中心に据えるべきであると考えられる。完全切除できれば完治する疾患であり，可能であれば極力切除するほうがよいが，犠牲にするものとのバランスが要求される。どこまで切除するかについては，本人，家族とよく話し合って決定する必要がある。

Ⅱ．外科的切除後の問題点と管理

外科的切除後には出血，創感染，神経損傷などの一般的に切除に伴う合併症が生じうる。それに加えて，前述のごとくリンパ管腫は完全切除を選択できない場合が多いが，その場合にはリンパ液に関連した合併症が起こりうる（図2）。

切除術時には断端の処理にリンパ漏を避ける最大の努力がなされるが[2,4]，それでもリンパ液が漏れて切除した部位に貯留する場合がある。一度貯まり始めるとなかなか軽快しない。圧迫にて改善が得られなければ，硬化療法時と同様にOK-432を注入して創内に強い炎症を惹起し，組織の硬化と癒着によりリンパ液貯留スペースを閉鎖する方法が有効である[3]。

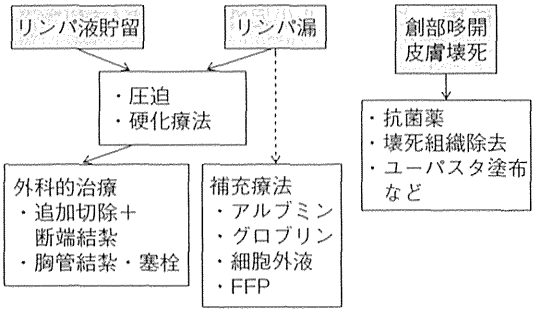

図2　リンパ管腫の非根治切除後合併症およびその治療
解説は本文内。

リンパ液の流出があまりに多い場合，貯留による圧排や創部哆開を生じうるため，ドレナージが必要となる。ドレナージ中は乳児でも1日1 *l* ほどのリンパ液流出を認めることがあり，容易に低蛋白血症（アルブミン，グロブリン）や低ナトリウム血症，低フィブリノーゲン血症をきたすため，補充療法を要する（図2）。また排液が乳びであれば，消化管で吸収したばかりの脂質も喪失するため，経静脈的脂質投与も必要となる。中心静脈カテーテルの留置を要することもある。硬化療法を行っても減少傾向を認めなければ，再度外科的切除と断端閉鎖を試みる。漏出部位を閉じ込めるように縫合閉鎖する。乳び漏出であれば，胸管結紮[5]や胸管塞栓[6]も場合により有効である。

体表皮下の病変を大きく切除すると薄くなった皮膚は壊死し，縫合線はリンパ漏により閉鎖せず，しばらくして哆開することがある。滲出が多く管理に難渋することは多い。われわれは，術後1週間以降に創哆開を生じ，滲出の管理に難渋した症例に対して，イソジン-シュガー（ユーパスタ®）を使用したところ，劇的に肉芽形成を認め急速に創閉鎖を得る経験をした。滲出の多い創部の肉芽形成に有効であることはよく知られているが[7]，リンパ管腫切除後の創部にも有効であると考えられた。

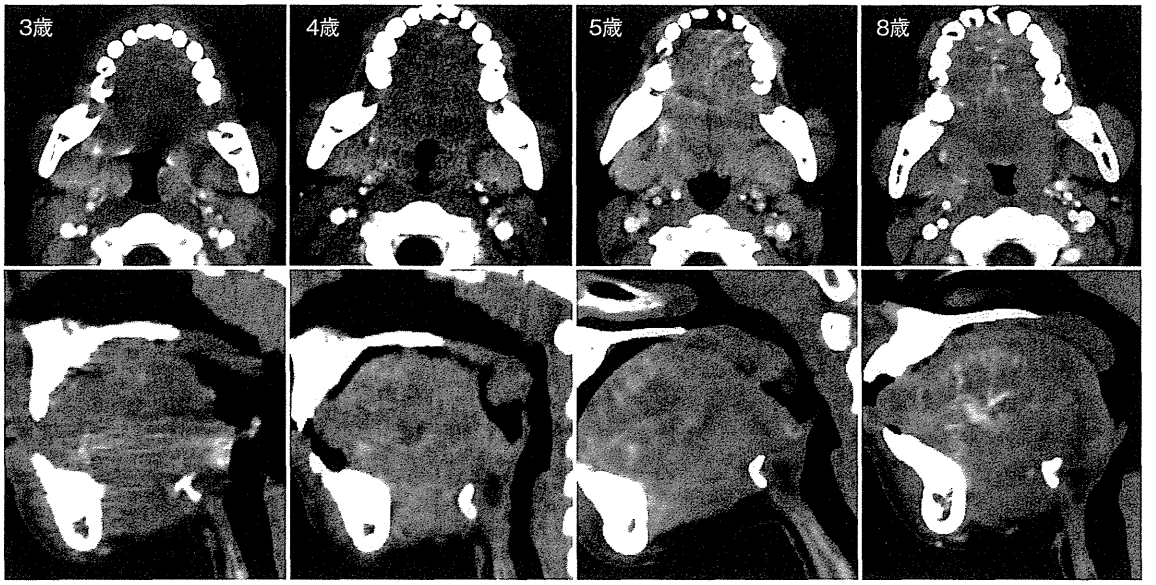

図 3 舌リンパ管腫内血管の経年変化（造影 CT）
舌表面付近の海綿状リンパ管腫の症例。経過観察中にリンパ管腫病変の深部に造影される血管の経時的な増生を認めた。

Ⅲ. 術後遠隔期の諸問題

リンパ管腫はほとんどが小児期の発症であり，治療は小児期から開始し，大規模な治療は小児期に行われることが多い。ある程度安定した状態を得るまで積極的治療を行ったのちは，それ以上の改善の余地がないと判断された個々のレベルで保存的加療時期へ移行する。完治すればなにも起こらないし，病変が残っていても落ち着いていて，通常問題にならなくなることもある。一方，炎症を中心としてその後も病変にさまざまな問題を生じ，治療を必要とする場合もある〔**図 1**（本項 1181 頁）〕。長期フォロー中の主な問題を以下にとりあげる。

1．感染（蜂窩織炎）

病変部の感染はなぜ起こるか，細菌はどこからくるのか，起因菌がなんなのか，正確な発症機序はわからないことが多い。蛋白質の豊富なリンパうっ滞は細菌の温床となると考えられるが，一度炎症が生じると，内出血，血流増加に伴いリンパの増加，うっ滞の悪化という悪循環を生じる（図 1）。抗菌薬投与は有効であるが，感染を抑えても組織のむくみが完全によくなる前に次の感染を生じたりするため，抑え込むのに難渋する。決め手はない。

2．出血

リンパ管腫は，慢性に炎症を繰り返していると，組織への血液流入が多くなり，結果的に内出血，出血が増えるようである（**図 3**）。巨大な病変周囲の皮下の静脈の異常な発達はよく認められる。リンパ管腫の嚢胞内への出血点は不明のことが多いが，リンパ嚢胞は壁に豊富な血管網を有しており，また比較的太い血管の周囲に発生していることが多いことと関係があると考えられる。

内出血後は，嚢胞内圧と血管内のバランスがとれるまで内圧が上昇してから止血すると考えられ，病変部は急速に腫脹し張りも強くなる。リンパ液は黒褐色に変色し，次第に病変内全域に広がるため，皮膚を通して青黒く透見される。早期に穿刺すると，再び出血することもある。一度大きな凝血塊を作るとなかなか消失しないが，多くの場合 echogenic な流動性のある血液・リンパ液の混合液となる。

それまで長期間つぶれていたリンパ管腫病変が内出血により急速増大した場合には，無治療でも数カ月内に再び縮小に転じ，元に戻ることが多い

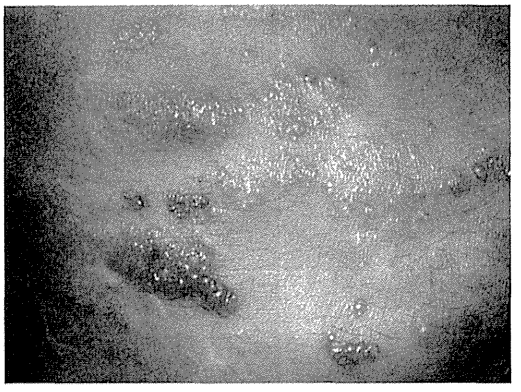

図 4 限局性リンパ管腫(lymphangioma circumscriptum)
側胸部の病変の写真。さまざまな程度の隆起性病変が孤立的に存在，もしくは集簇を形成している。左下の集簇性病変からはリンパ漏を認めることがある。

ので，すぐに硬化療法などを積極的にする必要はない。

3．皮膚・粘膜病変の出現（限局性リンパ管腫）

リンパ管腫は病変の部位を拡大することは通常ないが，時間の経過とともに皮下の病変や粘膜下の病変が表面に進展し，小さな嚢胞性病変が丘疹・結節を形成することがある。単発のこともあるし，集簇しカエルの卵状を呈することもある。この病変は限局性リンパ管腫（lymphangioma circumscriptum）とよばれる[8]（図 4）。外表・口腔粘膜・舌などによく認められ，内出血を生じ黒色に変色して整容性に大きな問題を生じる。また突出しているため擦過・圧迫され，リンパ瘻を生ずる。治療は OK-432 局注硬化療法，CO_2レーザー焼灼，液体窒素・ドライアイス療法[9]，無水エタノール局注[10]（臨床研究進行中：UMIN000011130）などであるが，表皮病変には有効だが，深部に大きな病変が残存する場合には再発は必至である。

4．リンパ漏

体表のリンパ漏は，限局性リンパ管腫に発症することが多い。常に認められるわけではないが，漏出が多いときには衣類を汚し，暑い時期には悪臭を発する。内出血後には，血液を混じたリンパ液となる。感染経路にもなると考えられる。陰部に限局性リンパ管腫病変を認め，鼠径輪や大腿輪を通して骨盤内後腹膜に病変が連なっており，立位で陰部より大量のリンパ漏を生じる同じタイプの症例がある。一度漏れが生じると表皮が修復されるまで止まらず，日に 2，3 *l* も排液するため，介護用紙おむつを当てて生活をしている。前項の限局性リンパ管腫に対する治療はこのような病変が深部広範にわたる重症例に対しては無効で，現時点では解決策がない。

5．乳び腹水・胸水

リンパ漏が体腔内に生ずる場合もある。後腹膜・腸間膜の広汎なリンパ管腫は，根治切除のためには大量の腸管と腸間膜を切除することになり，完全切除は断念されることが多いが，そのなかで慢性的に乳び腹水を生じる症例がある。また縦隔病変があり，同様に乳び胸水を発症する場合もある。これらはしばしば難治性で，とくに乳び胸水や心嚢液貯留をきたすような症例ではときに死にいたる。ただし，これらの症例は特異で，一般的に重症が多いリンパ管腫症の性質をもっているリンパ管腫，リンパ管腫症の境界上の症例と考えられる。

6．悪性腫瘍の発生について

リンパ管腫は悪性転化しないのかどうかは，病変を残して長期に経過をみていくうえで非常に重要な問題である。実際には，積極的に自然な悪性化を念頭におかねばならない根拠となるような症例報告や検討はない。リンパ管腫において異常を認めるリンパ管内皮細胞が悪性化したという報告は認められず，わずかに国外で血管芽細胞肉腫が発生したという 1 例報告[11]と国内で炎症を繰り返した症例からやはり血管系の悪性腫瘍が発生したとの報告がある（personal communication）。

7．気道狭窄の問題

気道狭窄症状は，頸部・縦隔に病変が存在する場合に，幼少時に生じやすい。とくに乳児期は組織が脆弱であり気道径自体も狭いため，病変内の出血や感染による急性腫脹により，咽頭部で容易に気道狭窄を生ずる。口腔・咽頭腔の狭窄は同時に経口摂取困難を生ずることもある。

しかし，成長とともに徐々に気道自体の拡大，脆弱性の改善を認めるため，物理的に気道狭窄を生じにくくなる。感染・出血などの急性増悪がなく安定した経過をたどり幼児期を過ぎると，主病

変に対する積極的な治療を止めても気管切開が不要となり，カニューレを抜去できる可能性がある。

8．経口摂取の問題

舌，咽喉頭周囲のリンパ管腫では，経口摂取が困難となることがある。生下時および幼年時にその傾向を示し，早期に胃瘻造設が行われることが多い。しかしながら，年齢とともに徐々に口腔・咽頭腔が確保されるようになると経口摂取は可能となることもある。経口摂取ができればQOLは大きく改善するため，なるべく早期からこの可能性を探りつつフォローアップをすべきである。

9．就学の問題

リンパ管腫の一部の重症患者にとって，就学は大きなハードルとなっている。とくに気管切開を施されている頸部・縦隔病変の子は，普通学級への進学に高いハードルがある。長期入院の環境ゆえの発達遅延や，発声・発語，聴力障害，咀嚼・嚥下困難，胃瘻造設状態などがあると，どれもが幼稚園，保育園，小中学校の入学時に問題とされる。居住地区の教育委員会との話し合いにて普通学級，養護学校，聾学校などさまざまなコースを歩むこととなる。就学後もさまざまな行事のたびに主治医は，学校側に患者の状態と行動制限を説明する必要がある。

また整容性についても，就学後につらい経験をすることは容易に想像されるが，医療側からの解決は困難なことが多い。就学前の可及的改善が望まれる。

10．トランジションの問題

さまざまな小児外科疾患患者の成人へのトランジションは，日本小児外科学会でも取り組んでいる難しい問題であるが，リンパ管腫もそういった疾患の一つである[12]。多くの成人した患者は，小児期から続けて同じ病院を受診しているようであるが，担当医の異動や自身の転居などにより，次の担当医を探すのが困難なことがある。また，しばらく安定期が続き通院を止めていたが，突然感染や出血などの症状が出た際に，新たに受診した成人の医療機関で疾患の治療経験がないという理由で診療を断られ，小児期に通っていた病院を受診するように勧められたりするようである。

11．行政による医療費助成制度

リンパ管腫およびリンパ管腫症のうち頸部・胸部の重症例は，2015（平成27）年より「慢性呼吸器疾患群」の一つとして小児慢性特定疾患に組み込まれることとなった。対象となる患者・家族にとっては朗報であろう。欲をいえば，上述したようにトランジションも問題となっている疾患であり，小児期を超えての補助があってもよいと考えられる。実は，リンパ管腫の重症・難治性患者は難病とされてしかるべきという訴えに対して，数年来厚生労働省は難治性疾患克服研究事業としてリンパ管腫に光をあて，実態調査を行ってきた。国の難病政策の転換期である現在，重症・難治性度に応じて難病の枠に入る可能性は示されており，厚生労働省の研究班がそのために必要な実務作業を進めている。

画期的な治療法が開発されないなか，少しでも患者の負担を減らし，また社会にこの疾患を認知してもらいたい。

おわりに

リンパ管腫の長期経過中にみられる，解決しがたいさまざまな問題点に触れた。リンパ管腫患者全体のごく一部ではあるが，小児外科医は長く患者とつきあっていくことになる。感染や出血，リンパ漏などの不安定状態の病変に対する確実な治療法は存在せず，炎症に対しては対症療法で治めているか，治まらないまま過ごしているのが現状である。長期的に病変の安定状態を目標として，さまざまな困難にあたっては，よく話し合って信頼関係を築きつつ診療に臨みたい。

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New *BRAF* knockin mice provide a pathogenetic mechanism of developmental defects and a therapeutic approach in cardio-facio-cutaneous syndrome

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Cardio-facio-cutaneous (CFC) syndrome is one of the 'RASopathies', a group of phenotypically overlapping syndromes caused by germline mutations that encode components of the RAS–MAPK pathway. Germline mutations in *BRAF* cause CFC syndrome, which is characterized by heart defects, distinctive facial features and ectodermal abnormalities. To define the pathogenesis and to develop a potential therapeutic approach in CFC syndrome, we here generated new knockin mice (here $Braf^{Q241R/+}$) expressing the *Braf* Q241R mutation, which corresponds to the most frequent mutation in CFC syndrome, Q257R. $Braf^{Q241R/+}$ mice manifested embryonic/neonatal lethality, showing liver necrosis, edema and craniofacial abnormalities. Histological analysis revealed multiple heart defects, including cardiomegaly, enlarged cardiac valves, ventricular noncompaction and ventricular septal defects. $Braf^{Q241R/+}$ embryos also showed massively distended jugular lymphatic sacs and subcutaneous lymphatic vessels, demonstrating lymphatic defects in RASopathy knockin mice for the first time. Prenatal treatment with a MEK inhibitor, PD0325901, rescued the embryonic lethality with amelioration of craniofacial abnormalities and edema in $Braf^{Q241R/+}$ embryos. Unexpectedly, one surviving pup was obtained after treatment with a histone 3 demethylase inhibitor, GSK-J4, or NCDM-32b. Combination treatment with PD0325901 and GSK-J4 further increased the rescue from embryonic lethality, ameliorating enlarged cardiac valves. These results suggest that our new *Braf* knockin mice recapitulate major features of RASopathies and that epigenetic modulation as well as the inhibition of the ERK pathway will be a potential therapeutic strategy for the treatment of CFC syndrome.

INTRODUCTION

Cardio-facio-cutaneous (CFC) syndrome is an autosomal dominant congenital anomaly syndrome, characterized by a distinctive facial appearance, short stature, congenital heart defects, intellectual disability and ectodermal abnormalities such as sparse, fragile hair, hyperkeratotic skin lesions and a severe generalized ichthyosis-like condition (1). The cardiac defects observed in CFC syndrome include pulmonary valve stenosis, hypertrophic cardiomyopathy and atrial septal defects. Increased nuchal translucency/fatal cystic hygroma colli due to lymphatic defects is also occasionally observed in affected individuals (2).

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Our group as well as another group has identified germline *BRAF* mutations in 50–75% of patients with CFC syndrome (3–6). Other known CFC-causative genes include *KRAS* as well as *MAP2K1* and *MAP2K2* (MEK1 and MEK2, respectively) (3–6), all located in the same RAS–MAPK pathway that regulates cell differentiation, proliferation, survival and apoptosis (7). Germline mutations associated with RAS–MAPK pathway components cause partially overlapping disorders, including Noonan syndrome, Costello syndrome, LEOPARD syndrome, neurofibromatosis type 1 and Legius syndrome (neurofibromatosis type 1-like syndrome). These syndromes are now collectively termed RASopathies or RAS–MAPK syndromes (8–10).

BRAF is a serine threonine kinase which regulates the RAS–MAPK signaling pathway. Somatic *BRAF* mutations have been identified in 7% of human tumors, including melanoma, papillary thyroid carcinoma, colon cancer and ovarian cancer (11). The *BRAF* V600E mutation, located in the catalytic kinase domain (conserved region (CR) 3 domain), accounts for 90% of all somatic *BRAF* mutations. In contrast, *BRAF* V600E mutation has not been identified in CFC syndrome. Germline *BRAF* mutations in CR3 kinase domain, including G464R, G469E and L597V, were overlapping those in somatic mutations (4,5,12,13). In contrast, germline mutations in the CR1 domain have been rarely identified in somatic cancers. The most frequent mutations identified in CFC syndrome patients are substitutions of the residue Gln257 (p.Q257R and p.Q257K) in the CR1 domain, which account for ~40% (13). Previous studies have shown that the activation of downstream signaling, including ELK transactivation, is weaker in cells expressing the Q257R mutation than in those expressing V600E (3).

Braf is ubiquitously expressed in murine organs at mid-gestation, and high levels of its expression are found in the brain and testes at adult stage (14,15). *Braf* knockout mice have been found to die at mid-gestation from vascular defects due to enlarged blood vessels and apoptotic death of dif ferentiated endothelial cells (16). Heterozygous knockin mice constitutively expressing V600E mutation have been found to exhibit embryonic lethality (17). Knockin mice expressing a hypomorphic *BRAF* V600E allele have been reported to show phenotypes partially overlapping those of CFC syndrome patients, including small size, craniofacial abnormalities and epileptic seizures (18). However, no mouse model for CFC syndrome expressing a *Braf* mutation in the CR1 domain has been generated and no therapeutic approach has been developed. In the present study, we generated knockin mice expressing CFC syndrome-associated *Braf* Q241R mutation, corresponding to *BRAF* Q257R mutation, in order to investigate the molecular pathogenesis and potential therapeutic possibilities for CFC syndrome.

RESULTS

Generation of a CFC syndrome mouse model

We have previously reported that the transcriptional activity of ELK, downstream of ERK, was enhanced by the transient overexpression of human *BRAF* Q257R in NIH3T3 cells (3). To verify whether the expression of mouse *Braf* Q241R enhances ELK transcription as *BRAF* Q257R, reporter assays were performed in NIH3T3 cells. The expression of *Braf* Q241R and that of V637E, which corresponds to *BRAF* V600E, were ~2.7- and 8.4-fold higher than that of *Braf* WT, respectively (Fig. 1A). These results suggest that the *Braf* Q241R mutation is a gain-of-function mutation, although the activation is weaker than that observed in *Braf* V637E.

To investigate the gain-of-function effect of the *Braf* Q241R mutation on development, *Braf* Q241R knockin mice were generated (Fig. 1B). The targeting vector (Fig. 1B) was electroporated into ES cells and targeted clones were identified by Southern blotting (Fig. 1C). Appropriate ES cells were injected into BALB/c blastocysts and chimeras were obtained from six independent ES cell clones (hereafter referred to as $Braf^{Q241R\ Neo/+}$). To induce ubiquitous expression of *Braf* Q241R in germ cells, the $Braf^{Q241R\ Neo/+}$ mice were crossed with CAG-Cre transgenic mouse ($Braf^{+/+}$; *Cre*) and genotyping was confirmed by PCR (Supplementary Material, Fig. S1). Furthermore, sequencing was performed to confirm that Cre recombination resulted in *Braf* Q241R expression (Fig. 1D).

To examine if cell signaling pathways, including ERK, JNK, p38 and PI3K–AKT pathways, were altered in $Braf^{Q241R/+}$; *Cre* embryos, western blotting analysis was performed using cell extracts derived from whole-mouse embryos and brain. Protein levels of BRAF, CRAF, phosphorylated MEK and ERK in $Braf^{Q241R/+}$; *Cre* whole embryos were similar to those of $Braf^{+/+}$; *Cre* (Fig. 1E; Supplementary Material, Table S1), whereas phosphorylated MEK protein levels were higher in the brain of $Braf^{Q241R/+}$; *Cre* embryos (Fig. 1F; Supplementary Material, Table S2). Unexpectedly, phosphorylated p38 and AKT (Thr308) protein levels were somewhat lower in $Braf^{Q241R/+}$; *Cre* whole embryos at embryonic day (E) 14.5 (Fig. 1E; Supplementary Material, Table S1). These results suggest that $Braf^{Q241R/+}$; *Cre* embryos at E14.5 show a decrease of phosphorylated p38 and AKT (Thr308) protein levels.

Germline expression of *Braf* Q241R results in embryonic/neonatal lethality

Genotype analysis of embryos from an intercross between $Braf^{+/+}$; *Cre* and $Braf^{Q241R\ Neo/+}$ mice showed no surviving $Braf^{Q241R/+}$; *Cre* littermates at weaning, whereas $Braf^{+/+}$, $Braf^{+/+}$; *Cre* and $Braf^{Q241R\ Neo/+}$ littermates survived (Table 1). A normal Mendelian ratio was observed by E14.5. However, the survival rate of $Braf^{Q241R/+}$; *Cre* embryos dropped after E16.5. At E16.5, ~9.8% of embryos (4 of 41) were grossly hemorrhagic and edematous such as nuchal translucency (Fig. 2A, Table 1). Other $Braf^{Q241R/+}$; *Cre* embryos appeared normal (Fig. 2B) with no difference in body weight (data not shown). $Braf^{Q241R/+}$; *Cre* embryos, which were delivered by cesarean section at E18.5 and E19.5, remained pale and without movement or gasped for breath with cyanotic appearance, resulting in death within a few hours. A few embryos showed mandibular hypoplasia (2 of 39, 5.1%) and kyphosis (Fig. 2C and D).

Gross observation showed increased heart size in $Braf^{Q241R/+}$; *Cre* embryos at E16.5. At E18.5, $Braf^{Q241R/+}$; *Cre* embryos revealed severe peripheral liver necrosis (15 of 17, 88%) with decreased liver size and liver weight (Fig. 2E; Supplementary Material, Fig. S2). At E16.5, decreased liver weight was already observed (data not shown), although the gross appearance of the liver appeared normal. To examine if delayed lung maturation causes neonatal lethality, the histology of lung in

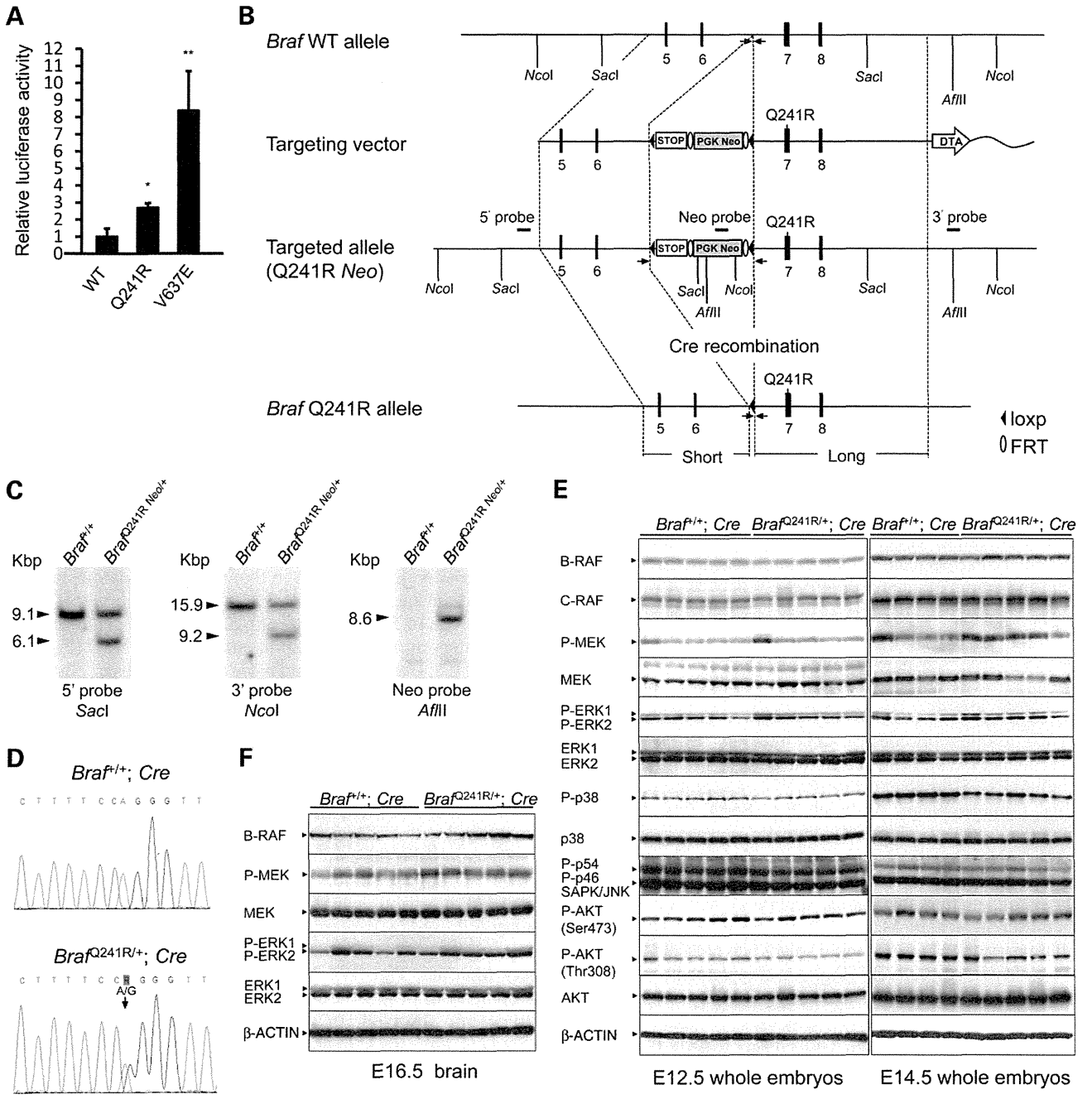

Figure 1. Generation of *Braf* Q241R knockin mice. (**A**) NIH 3T3 cells were transfected with the ELK1-GAL4 vector, the GAL4-luciferase trans-reporter vector, phRLnull-luc control vector and each mouse *Braf* expression plasmid, and reporter activities were determined as described in Materials and Methods. Luciferase activities were normalized with phRLnull-luc activities, containing distinguishable *R. reniformis* luciferase. Data are the means ± SD ($n = 4$). p.V637E in mouse *Braf* corresponds to oncogenic p.V600E in human *BRAF*. *, $P < 0.05$, **, $P < 0.01$ versus WT. WT, wild type. (**B**) Exons (solid boxes), PGK-Neomycin (PGK-Neo) cassette (gray box), STOP transcriptional sequences (open box), loxp sites (arrowheads) and Flp recombination target sites (ellipses) are indicated. Cleavage sites for diagnostic enzymes (*Sac*I, *Nco*I and *Afl*II) and the probes (5′-, 3′- and Neo probe) used to identify the homologous recombination are indicated. The PGK-Neo cassette was removed by crossing with CAG-Cre transgenic mice ($Braf^{+/+}$; *Cre*). The arrow indicates the positions of PCR primers used for genotyping of positive ES cells and mice. p. Q241R in mouse *Braf* corresponds to p.Q257R in human *BRAF*. DTA, diphtheria toxin A. (**C**) Southern blotting of ES cell clones. Genomic DNA from $Braf^{+/+}$ and $Braf^{Q241R\ Neo/+}$ ES cells was digested with *Sac*I (5′ probe), *Nco*I (3′ probe) or *Afl*II (Neo probe) and subjected to Southern blotting with a 5′, 3′ or Neo probe. The 5′, 3′ or Neo probe detects the 9.1-kb (*Braf* WT) and 6.1-kb ($Braf^{Q241R\ Neo/+}$) *Sac*I fragments, the 15.9 kb (*Braf* WT) and 9.2 kb ($Braf^{Q241R\ Neo/+}$) *Nco*I fragments or the 8.6 kb ($Braf^{Q241R\ Neo/+}$) *Afl*II fragment, respectively. (**D**) RNA was isolated from the brain of $Braf^{+/+}$; *Cre* and $Braf^{Q241R/+}$; *Cre* embryos at E18.5, and reverse transcribed into cDNA. Sanger sequencing was carried out using the cDNA. The arrow indicates the Q241R mutation in *Braf* exon 7. (**E** and **F**) Protein extracts from whole-mouse embryos (E12.5 and E14.5) and brain (E16.5) ($n = 4–5$ of each genotype) were subjected to western blotting with the indicated antibodies. β-Actin is shown as a loading control. The arrowheads indicate the bands corresponding to each protein.

Table 1. Genotyping of pups resulting from intercross between *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R\ Neo/+}$ mice

Age	*Braf*$^{+/+}$	*Braf*$^{+/+}$; *Cre*	*Braf*$^{Q241R\ Neo/+}$	*Braf*$^{Q241R/+}$; *Cre*	*n*	*P*
E12.5	24	29	23	23	99	0.80
E13.5	5	14	6	6 (2 [1])	31	0.08
E14.5	19	22 (1)	23	11 (1 [1])	75	0.19
E16.5	57	60	55	34 (7 [4])	206	0.04
E18.5	16	23	20	0 (17 [4])	59	<0.0001
E19.5	11	16	11	0 (11 [1])	38	<0.01
Weaning (P21)	56	54	56	0	166	<0.0001
Expected	25%	25%	25%	25%		

Deviation from the expected Mendelian ratios was assessed by the χ^2 test. The number of dead embryos is shown in parentheses. The number of edematous embryos is shown in brackets. P: postnatal day.

Braf$^{Q241R/+}$; *Cre* embryos was examined at E18.5 and E19.5. Lungs of the mutant embryos appeared normal and were able to inflate, but ~11.1% of embryos (1 of 9) showed alveolar hemorrhage (Supplementary Material, Fig. S3). Thyroid transcription factor-1 (TTF-1; lung epithelial cells marker), pro-surfactant protein C and PAS staining showed similar levels in *Braf*$^{Q241R\ Neo/+}$ and *Braf*$^{Q241R/+}$; *Cre* embryos (Supplementary Material, Fig. S4), suggesting that lung development and maturation are normal. Gross observation suggests that *Braf*$^{Q241R/+}$; *Cre* embryos show embryonic/neonatal lethality, cardiomegaly, liver necrosis, edema and craniofacial abnormalities.

Braf$^{Q241R/+}$; *Cre* embryos display various heart defects

Because *Braf*$^{Q241R/+}$; *Cre* embryos showed cardiomegaly and liver necrosis, possibly due to heart failure (Fig. 2E), detailed histological analysis of the heart at different embryonic stages was conducted. At E12.5, the hearts of *Braf*$^{Q241R/+}$; *Cre* embryos appeared normal (Supplementary Material, Fig. S5A), but showed an enlarged pulmonary valve and a dramatic increase in the density of trabeculae (hypertrabeculation) at E14.5 (Supplementary Material, Fig. S5B). At E16.5, 13 of 14 (93%) *Braf*$^{Q241R/+}$; *Cre* embryos (excluding edematous embryos) had various heart defects (Supplementary Material, Tables S3 and S4). Hypertrophy of pulmonary, tricuspid and mitral valves was present in 7, 8 and 9 of 14 embryos, respectively (Fig. 3A; Supplementary Material, Tables S3 and S4). In particular, hypertrophy in pulmonary valve leaflets was prominent, plugging the entire space of the pulmonary valve ring (Fig. 3B). Other heart defects observed in *Braf*$^{Q241R/+}$; *Cre* embryos included ventricular septal defect (VSD) in 2 of 14 embryos (Fig. 3A), abnormal endocardial cushion in 2 (Fig. 3A), hypertrabeculation in 3 (Fig. 3A), epicardial blisters in 2 (Fig. 3A and C), a thickened trabecular layer and thinned compact layer in the left, right or combined myocardium (noncompaction: one case of cardiomyopathy accompanied by cardiac hypertrophy) in 4 (Fig. 3D) and hypoplasia of the coronary arteries in 3. The ventricular radius and the thickness of the pulmonary and tricuspid valves were significantly higher in *Braf*$^{Q241R/+}$; *Cre* embryos, suggesting cardiac enlargement and thickened pulmonary and tricuspid valves (Fig. 3E). These results suggest that *Braf*$^{Q241R/+}$; *Cre* embryos develop various congenital heart defects, which almost certainly contributes to embryonic lethality.

Braf$^{Q241R/+}$; *Cre* embryo hearts exhibit enhancement of cell proliferation, ERK signaling activation and decrease of phosphorylated p38 and AKT

To examine if heart defects observed in *Braf*$^{Q241R/+}$; *Cre* embryos are caused by increased cell proliferation and/or reduced cell death, cell proliferation was analyzed by phosphohistone H3 (pHH3) immunostaining and cell death by TUNEL assay. At E13.5, regarding heart abnormalities in each embryos, the number of pHH3-positive-stained cells varied. pHH3-positive-stained cells in the interventricular septum and myocardium increased in *Braf*$^{Q241R/+}$; *Cre* embryos (Fig. 4A and B). At E16.5, the nucleus of pHH3-positive cells increased in the interventricular septum in embryos with VSD (Fig. 4C). *Braf*$^{Q241R/+}$; *Cre* embryos had more pHH3-positive cells in pulmonary valves (Fig. 4D). In contrast to cell proliferation, hardly any cells undergoing apoptosis were observed in either *Braf*$^{+/+}$; *Cre* or *Braf*$^{Q241R/+}$; *Cre* at E13.5 and E16.5 (data not shown). These results suggest that the cell proliferation state depends on heart abnormalities in each embryo at E16.5 and that the increased staining for pHH3 in the interventricular septum was associated with VSD.

To examine if the cardiac signaling pathways were altered in *Braf*$^{Q241R/+}$; *Cre* embryos, the activation of kinases was screened in various signaling pathways using a phospho-kinase array followed by western blotting of the lysates from hearts of *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5 (Fig. 4E and F; Supplementary Material, Fig. S6). No changes in phosphorylated ERK protein levels in both the phospho-kinase array and western blotting were observed. In contrast, phosphorylated p38, AKT (Ser473) and AKT (Thr308) protein levels, which are not direct targets of BRAF, were relatively lower in *Braf*$^{Q241R/+}$; *Cre* embryos than in *Braf*$^{+/+}$; *Cre*, which was confirmed by western blotting. To verify the activation of transcription factors downstream of ERK, the expression of ELK1 and the PEA3 (polyoma enhancer activator 3) subfamily Ets transcription factors were examined by quantitative real-time PCR, these expressions being known as transcriptional targets of FGF signaling-mediated activation of ERK in heart and oncogenic BRAF signaling in melanoma (19,20). At E13.5, E16.5 and E18.5, cardiac mRNA levels of *Etv1*, *Etv4* and *Etv5*, but not *Elk1*, were significantly higher in *Braf*$^{Q241R/+}$; *Cre* embryos than those in *Braf*$^{+/+}$; *Cre* (Fig. 4G; Supplementary Material, Fig. S7). Next, we investigated the influence of genes responsible for hypertrophic cardiomyopathy and

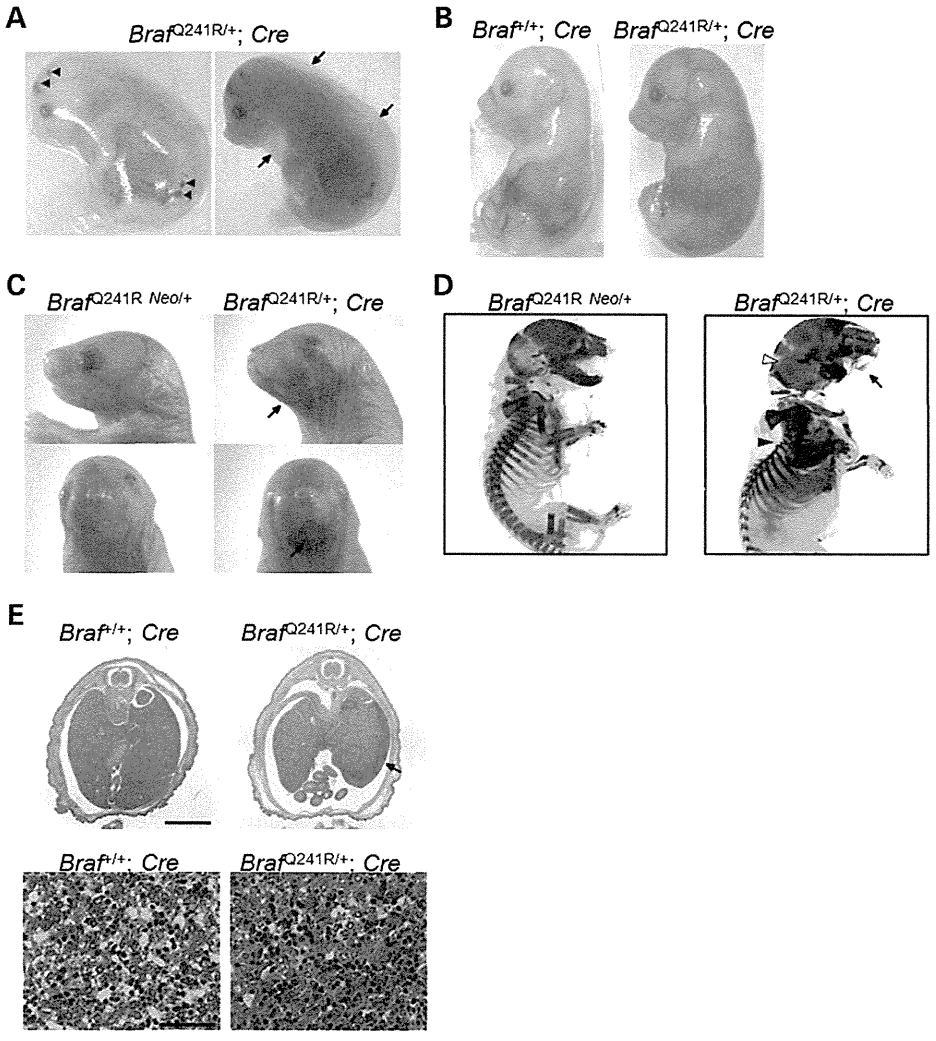

Figure 2. Lethal phenotypes of *Braf*$^{Q241R/+}$; *Cre* embryos. (**A** and **B**) Gross appearance of *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5. (A) Arrowheads and arrows indicate hemorrhage and edema, respectively. The right panel shows *Braf*$^{Q241R/+}$; *Cre* embryos with transmitted illumination. (**C**) Craniofacial structure of *Braf*$^{Q241R\ Neo/+}$ and *Braf*$^{Q241R/+}$; *Cre* embryos at E19.5. The arrow indicates mandibular hypoplasia. (**D**) Alcian Blue/Alizarin Red staining of *Braf*$^{Q241R\ Neo/+}$ and *Braf*$^{Q241R/+}$; *Cre* embryos at E19.5. The arrow, solid arrowhead and open arrowhead indicate mandibular hypoplasia, kyphosis and ossification in the interparietal bone, respectively. (**E**) H&E staining of liver sections of *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E18.5. The arrow indicates hepatic necrosis. The lower panel shows higher magnification views of hepatic necrosis. Scale bars in upper panels = 200 μm and in lower panels = 50 μm.

cardiac development in *Braf*$^{Q241R/+}$; *Cre* embryos at E18.5, which exhibited a cardiomyopathy phenotype, such as cardiac enlargement and noncompaction (Fig. 3D and E) and structural abnormalities, including VSD. No differences in mRNA levels of cardiomyopathy-specific genes (*Myh6* and *Myh7)* and genes related to the heart formation and development (*Gata4* and *Nkx2.5*) were observed (Fig. 4G). These results suggest that ERK activation, including increased mRNA levels of Ets transcription factors, and decreased levels of p38 and AKT exist in heart tissues of *Braf*$^{Q241R/+}$; *Cre* embryos.

Braf$^{Q241R/+}$; *Cre* embryos develop lymphangiectasia

Patients with RASopathies, including CFC syndrome and Noonan syndrome, exhibit nuchal translucency, which is subcutaneous fluid collection in the fetal neck visualized by ultrasonography. Nuchal translucency is caused by distended jugular lymphatic sacs (JLSs), which result from a disturbance in differentiation of lymphatic endothelial cells (21,22). We hypothesized that the hemorrhage and edema in *Braf*$^{Q241R/+}$; *Cre* embryos may be caused by defective lymphatic development. Histological examination revealed distended and blood-filled JLSs in *Braf*$^{Q241R/+}$; *Cre* embryos but not in *Braf*$^{+/+}$; *Cre* embryos at E12.5 and E16.5 (Fig. 5A and B; Supplementary Material, Fig. S8A). The primary lymphatic sacs are remodeled to produce a hierarchically organized network of lymphatic capillaries and collecting lymph vessels at stages between E14.5 and postnatal stages (23). The JLSs are hardly observed in mouse embryos at E16.5. In *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5, cavities such as the JLSs of mouse embryos from E12.5 to E14.5 were observed (Fig. 5B), suggesting defective lymphatic development from the cardinal vein in *Braf*$^{Q241R/+}$; *Cre*

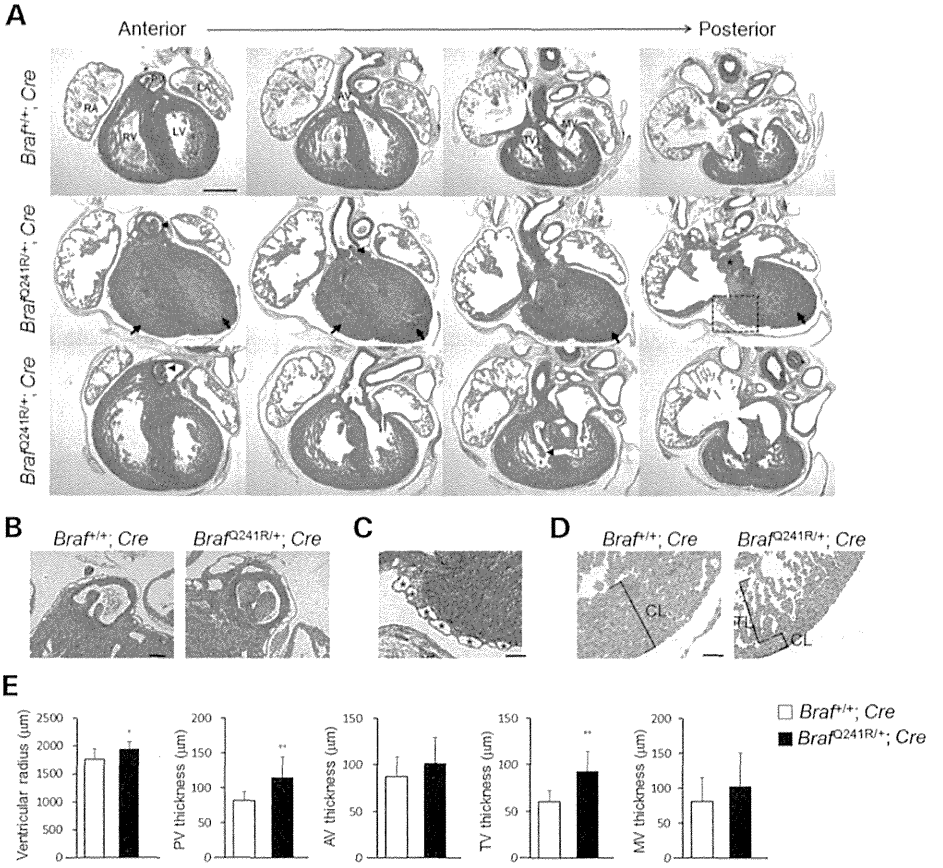

Figure 3. Cardiac phenotype of *Braf*$^{Q241R/+}$; *Cre* embryos. (**A**–**D**) H&E staining of sequential anterior to posterior sections of embryonic hearts from *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* at E16.5. A dramatic increase in density of trabeculae (arrows), enlarged valves (solid arrowheads), VSD (open arrowhead) and abnormal endocardial cushion (asterisk) are observed. Scale bars 500 μm (A) and 100 μm (B–D). (B) Higher magnification of the pulmonary valves in *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos. (C) Higher magnification of the boxed region in Figure 3A showing the epicardial blisters (asterisks) in *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5. (D) Representative image of noncompaction in hearts from *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5. (**E**) The ventricular radius and the thicknesses of the cardiac valve leaflets were measured at their largest diameter in serial sections of *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5. Data are the means ± SD (*Braf*$^{+/+}$; *Cre* ($n = 9$) and *Braf*$^{Q241R/+}$; *Cre* ($n = 14$)). $^{*}P < 0.05$, $^{**}P < 0.01$ versus *Braf*$^{+/+}$; *Cre*. LV, left ventricle; RV, right ventricle; LA, left atrium; RA, right atrium; PV, pulmonary valve; AV, aortic valve; TV, tricuspid valve; MV, mitral valve; CL, compact layer; TL, trabecular layer.

embryos. To examine the network formation of blood and lymphatic vessels, we performed immunostaining using antibodies against lymphatic vessel endothelial hyaluronan receptor 1 (LYVE-1; lymphatic endothelial cell-specific marker), α-SMA for staining of vessels with smooth muscle and CD31 (platelet-endothelial cell adhesion molecule-1, PECAM-1) for staining of vascular endothelial cells. At E12.5, the cells lining JLSs in both *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos were positive for LYVE-1 (Fig. 5C), whereas slightly CD31-positive cells were detected in JLSs and the jugular vein (Fig. 5D). No α-SMA expression was observed (Supplementary Material, Fig. S8B). At E16.5, the cavities such as the JLSs in *Braf*$^{Q241R/+}$; *Cre* embryos were negative for LYVE-1, α-SMA and CD31 (Fig. 5E; Supplementary Material, Fig. S8C and D), but the subcutaneous lymphatic vessels were markedly positive for LYVE-1 (Fig. 5F; Supplementary Material, Fig. S8E). These results indicate that *Braf*$^{Q241R/+}$; *Cre* embryos show defective lymphatic development from the cardinal vein, leading to distention of the JLSs, dilated lymphatic vessels and edema.

Treatment with a MEK inhibitor and/or histone demethylase inhibitors prevents embryonic lethality in *Braf*$^{Q241R/+}$; *Cre* embryos

MEK inhibitor, PD0325901, treatment is known to rescue the embryonic lethality of Noonan syndrome model mice (24). Pregnant *Braf*$^{+/+}$; *Cre* mice were treated with various compounds to see whether this would result in recovery from embryonic lethality (Table 2). Male *Braf*$^{Q241R\ Neo/+}$ mice were crossed with female *Braf*$^{+/+}$; *Cre* mice, and pregnant mice were intraperitoneally injected with dimethylsulfoxide (vehicle), PD0325901 [0.5 or 1.0 mg of body weight (mg/kg)], MAZ51 (VEGFR3 inhibitor; 1.0, 2.0 or 5.0 mg/kg), sorafenib (BRAF, VEGFR, PDGFR multikinase inhibitor; 5.0 mg/kg), lovasatin (HMG-CoA reductase and farnesyl transferase inhibitor; 5.0 mg/kg) or everolimus (mTOR inhibitor; 0.1 mg/kg), daily from E10.5 to E18.5. PD0325901 treatment (0.5 mg/kg) modestly rescued the embryonic lethality of *Braf*$^{Q241R/+}$; *Cre* mice (2 of 30). Seven embryos also survived for 3 weeks with

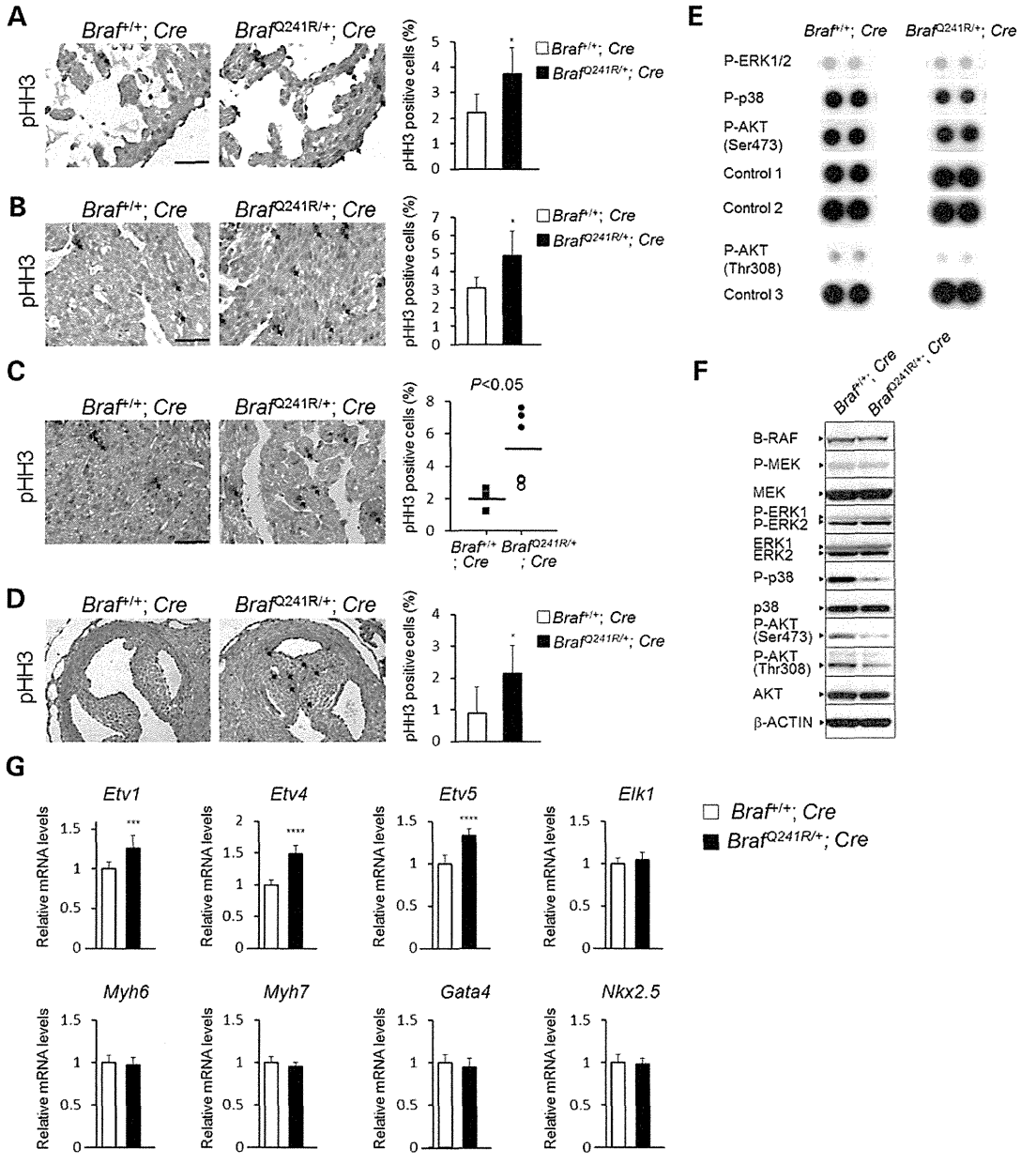

Figure 4. Increased cell proliferation and altered multiple signaling pathways in *Braf*$^{Q241R/+}$; *Cre* embryo hearts. (**A**–**D**) Immunostaining for pHH3 in the myocardium (A), interventricular septum (B and C) and pulmonary valves (D) of *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E13.5 (A and B) and E16.5 (C and D). The arrows indicate representative positive cells. *Braf*$^{Q241R/+}$; *Cre* embryos with or without VSD are shown in closed cycles or open circles, respectively. Scale bars 50 μm (A–C). Data are means ± SD (A and B) *Braf*$^{+/+}$; *Cre* ($n = 5$) and *Braf*$^{Q241R/+}$; *Cre* ($n = 5$). (C and D) *Braf*$^{+/+}$; *Cre* ($n = 3$) and *Braf*$^{Q241R/+}$; *Cre* ($n = 6$). $^{*}P < 0.05$ versus *Braf*$^{+/+}$; *Cre*. (**E**) Protein extracts (400 μg) of the hearts from *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5 were subjected to Phospho-Kinase Antibody Array. Results are representative of gene spots that showed significant changes in 45 phosphorylated proteins. (**F**) Western blotting of the hearts from *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5 (pooled samples; *Braf*$^{+/+}$; *Cre* ($n = 5$), *Braf*$^{Q241R/+}$; *Cre* ($n = 5$)). β-Actin is shown as a loading control. The arrowheads indicate the bands corresponding to each protein. (**G**) Cardiac mRNA levels were determined by quantitative reverse transcription–PCR. mRNA levels were normalized by those of *Gapdh*, and those in *Braf*$^{+/+}$; *Cre* at E18.5 are set at 1. Data are the means ± SD (*Braf*$^{+/+}$; *Cre* ($n = 10$) and *Braf*$^{Q241R/+}$; *Cre* ($n = 6$)). $^{***}P < 0.001$, $^{****}P < 0.0001$ versus *Braf*$^{+/+}$; *Cre*. *Etv1*, *Etv4*, *Etv5*, *Myh6* and *Myh7* encode ER81, Pea3, ERM, α-MHC and β-MHC, respectively.

prenatal treatment of PD0325901 (1.0 mg/kg) (7 of 37, $P = 0.32$, χ^2 test for deviation from the Mendelian ratios). PD0325901-treated *Braf*$^{Q241R/+}$; *Cre* embryos appeared normal without edema and mandibular hypoplasia (0 of 31 at E16.5 to P0), whereas other genotype mice, excluding *Braf*$^{Q241R/+}$; *Cre* treated with PD0325901, showed teratogenic effects, including open eyes (Supplementary Material, Fig. S9), edema, enlarged semilunar valves and atrioventricular valves (data not shown). Other compounds had no effect on the recovery of embryonic lethality in *Braf*$^{Q241R/+}$; *Cre* embryos.

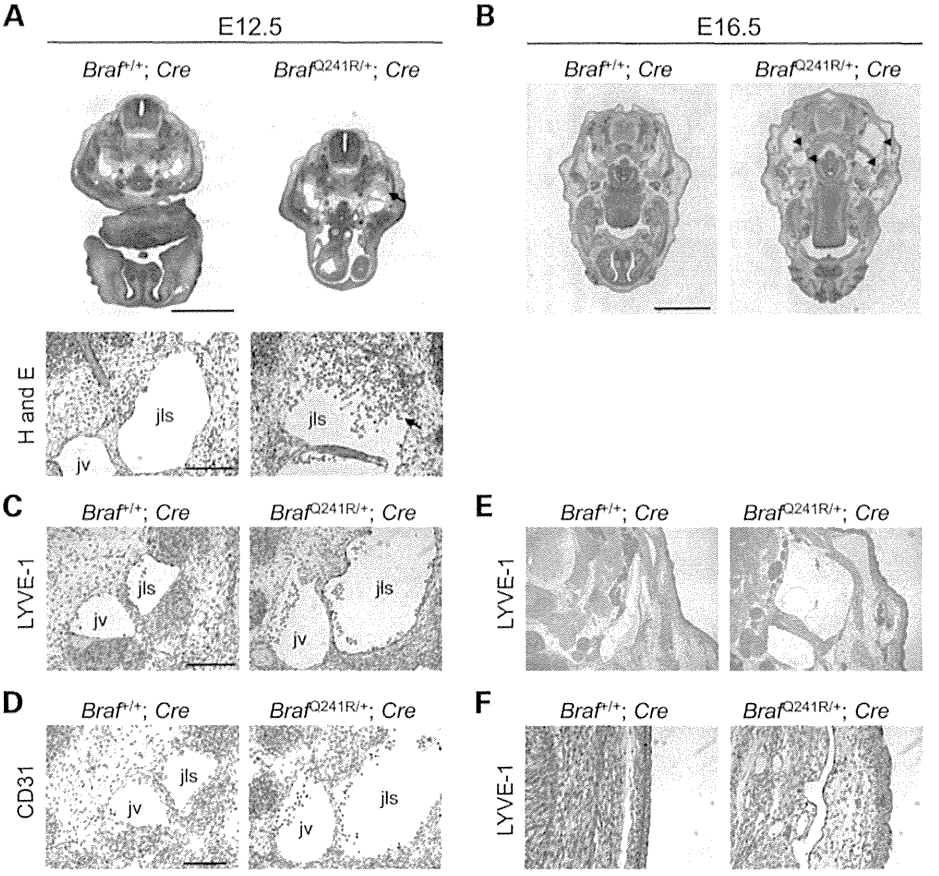

Figure 5. Abnormal lymphatic development in *Braf*$^{Q241R/+}$; *Cre* embryos. (**A** and **B**) Transverse sections of *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E12.5 (A) and E16.5 (B) stained with H&E. Lower panels show high-magnification views of jugular lymph sac (A). The arrows (A) and arrowheads (B) indicate blood cells in jugular lymph sacs and the regions which are similar to the jugular lymph sacs or jugular veins of embryos at E12.5, respectively. Scale bars 1 mm (in upper panels, A), 100 μm (in lower panels, A) and 2 mm (B). (**C**–**F**) Sections of *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E12.5 (C and D) and E16.5 (E and F) stained with antibodies against lymphatic endothelial markers, LYVE-1 (C, E and F) or CD31 (D). (F) Subcutaneous lymphatic vessels. jls, jugular lymph sac; jv, jugular vein.

Thus, PD0325901 treatment prevented embryonic lethality in *Braf*$^{Q241R/+}$; *Cre* embryos and could ameliorate edema and mandibular hypoplasia.

Epigenetic regulation of gene expression, such as histone acetylation and histone methylation, plays a crucial role in the transcriptional regulation of cell differentiation, development, the inflammatory response and cancer (25). Recently, a histone deacetylase inhibitor, SAHA [vorinostat (Zolinza)], has been used in the treatment of lymphomas and solid tumors. Recent studies have suggested the association of UTX and JMJD3, a histone H3 lysine 27 (H3K27) demethylase, with heart development (26–28). We therefore tested whether treatment using these compounds leads to the rescue of embryonic lethality (Table 2). SAHA treatment had no effect (data not shown); however, one embryo survived for 3 weeks with prenatal treatment of GSK-J4 (inhibitors of histone H3K27 demethylase UTX and JMJD3; 5.0 mg/kg) (25) or NCDM-32b (inhibitor of histone H3K9 demethylase JMJD2C; 5.0 mg/kg) (29). Moreover, co-treatment with GSK-J4 (5.0 mg/kg) and PD0325901 (0.5 mg/kg) further increased the number of *Braf*$^{Q241R/+}$; *Cre* mice alive at weaning (5 of 31, $P = 0.14$). The teratogenic effects, which were frequently observed in PD0325901 treatment, were not observed in the co-treatment with GSK-J4 and PD0325901.

We further investigated whether co-treatment with PD0325901 and GSK-J4 prevented heart defects in *Braf*$^{Q241R/+}$; *Cre* embryos. Co-treatment with PD0325901 and GSK-J4, but not PD0325901 treatment (1.0 mg/kg) alone, ameliorated enlarged pulmonary, tricuspid and mitral valves in *Braf*$^{Q241R/+}$; *Cre* embryos (Fig. 6A and B). However, no difference in the frequency of heart defects, including VSD, hypertrabeculation, epicardial blisters and non-compaction, was observed. It is noteworthy that treatment with PD0325901 or GSK-J4 alone or the co-treatment reversed the decrease of phosphorylated p38 protein levels (Fig. 6C; Supplementary Material, Fig. S10). These results suggest that combination treatment with PD0325901 and GSK-J4 prevents embryonic lethality, enlarged cardiac valves and decreased phosphorylated p38 in *Braf*$^{Q241R/+}$; *Cre* embryos.

DISCUSSION

In this study, we generated heterozygous *Braf* Q241R-expressing mice, which exhibited embryonic and postnatal lethality due to liver necrosis, skeletal abnormalities, lymphatic defects and various cardiac defects, including cardiomegaly, non-compaction, enlarged cardiac valves and hypertrabeculation.

Table 2. Rescue of embryonic lethality in *Braf*$^{Q241R/+}$; *Cre* embryos by MEK inhibitor, histone demethylase inhibitor or these combined treatment

Compound	Dose (mg/kg body weight)	Genotype (3 weeks) *Braf*$^{+/+}$	*Braf*$^{+/+}$; *Cre*	*Braf*$^{Q241R\ Neo/+}$	*Braf*$^{Q241R/+}$; *Cre*	n^a	n^b	n^c	*P*
DMSO (vehicle)	–	14	8	8	0	30	6	5.0	<0.01
PD0325901	0.5	7	14	7	2	30	13	2.3	0.02
	1.0	11	13	6	7	37	14	2.6	0.32
MAZ51	1.0	9	8	11	0	28	6	4.7	0.02
	2.0	10	14	7	0	31	6	5.2	<0.01
	5.0	10	7	11	0	28	11	2.5	0.01
Sorafenib	5.0	12	15	8	0	35	13	2.7	<0.01
Lovastatin	5.0	8	19	17	0	44	10	4.4	<0.01
Everolimus	0.1	6	6	9	0	21	9	2.3	0.04
NCDM-32b	2.0	12	4	9	0	25	9	2.8	<0.01
	5.0	10	10	14	1	35	11	3.2	0.02
	10.0	11	10	19	0	40	9	4.4	<0.01
GSK-J4	5.0	8	18	14	1	41	11	3.7	<0.01
	10.0	16	26	20	0	62	23	2.7	<0.01
PD0325901 + GSK-J4	0.5 + 5.0	8	13	5	5	31	10	3.1	0.14

Male *Braf*$^{Q241R\ Neo/+}$ mice were crossed with female *Braf*$^{+/+}$; *Cre* mice, and pregnant mice were intraperitoneally injected with vehicle or various compounds shown daily from E10.5 to E18.5. Deviation from the expected Mendelian ratios was assessed by χ^2 test. n^a, the total number of acquired pups. n^b, the total number of treated female *Braf*$^{+/+}$; *Cre* mice. n^c, the average number of survived pups at weaning (n^a/n^b).

Increased expression of Ets transcription factors and decreased expression of cardiac phosphorylated p38 in embryonic heart tissues were observed. PD0325901 treatment, in part, rescued embryonic and postnatal lethality in *Braf*$^{Q241R/+}$; *Cre* mice. One pup in *Braf*$^{Q241R/+}$; *Cre* also survived until P21 with treatment of GSK-J4 or NCDM-32b. PD0325901 treatment, but not GSK-J4 and NCDM-32b treatment, ameliorated edema and mandibular hypoplasia. Moreover, PD0325901 co-treatment with GSK-J4 further rescued embryonic lethality with recovered hypertrophy of pulmonary, tricuspid and mitral valves and the decreased expression of phosphorylated p38. Taken together, mice expressing a development-specific *Braf* Q241R mutation will be useful to further clarify the pathogenesis of CFC syndrome and to develop therapeutic approaches.

Patients with RASopathies are characterized by generalized abnormalities of lymphatic development. Fetuses with RASopathies have been shown to be characterized by hydrops, pleural effusions, increased nuchal translucency due to distended JLS and cystic hygroma in utero (30–32). Children and adults with RASopathies show generalized lymphedema, peripheral lymphoedema or pulmonary lymphangiectasia (33). Our new model, *Braf*$^{Q241R/+}$; *Cre* mice, showed embryonic and postnatal lethality and exhibited multiple developmental defects in the lymphatic system, including hydrops, distended JLS and subcutaneous lymphatic vessels. In contrast, mice of other knockin mouse models for RASopathies survived to adulthood and have not shown the defects in lymphatic system (34–36). Thus, for the first time our new model *Braf*$^{Q241R/+}$; *Cre* mice demonstrated the developmental lymphatic defects, which are the common features observed in RASopathies, in knockin mouse models for RASopathies.

Dysregulation of the RAS–MAPK pathway is a common underlying mechanism of RASopathies. However, a variety of compounds, including the RAS–MAPK pathway and other signaling pathways, has been effective for ameliorating the defects in previous knockin mouse models of RASopathies. MEK inhibitors have been found to ameliorate the cardiac defects and skeletal features in mice expressing *SOS1* and *RAF1* mutations (24,35). Angiotensin II inhibitor ameliorates the phenotypes of hypertension, vascular remodeling and fibrosis of the kidney and heart in mice expressing *HRAS* G12V mutation (36), and mTOR inhibitor ameliorates hypertrophic cardiomyopathy in a mouse model of LEOPARD syndrome, expressing a catalytically inactive mutation in SHP2 (34). We examined a variety of compounds, including anti-cancer agents, MEK inhibitor, mTOR inhibitor, VEGFR3 inhibitor, BRAF inhibitor and farnesyl transferase inhibitor using our *Braf*$^{Q241R/+}$; *Cre* mice. Treatment with MEK inhibitor, but not mTOR inhibitor, in *Braf*$^{Q241R/+}$; *Cre* mice ameliorated embryonic lethality and skeletal abnormalities, suggesting that the pathogenesis of the disease is similar to those in *SOS1* and *RAF1* mutations. Thus, our new *Braf*$^{Q241R/+}$; *Cre* mice will be useful to screen various compounds for therapeutic approaches to RASopathies.

The exact mechanisms by which the single treatment of histone demethylase inhibitor or co-treatment of MEK inhibitor and histone demethylase inhibitor were effective for *Braf*$^{Q241R/+}$; *Cre* mice have not yet been characterized. Lysine modification of histone 3, acetylation and methylation, is associated with gene activation or silencing (37). In gene expression, inactive genes show methylation at lysine 27, and permanently silenced genes frequently are characterized by methylation at lysine 9 (37). Histone H3K27 methylase, *Ezh2*, conditional knockout mice in cardiomyocytes have been reported to show abnormal heart development, such as noncompaction and excessive trabeculation (38). Meanwhile, deletion of histone H3K27 demethylase, UTX, has been identified in individuals with Kabuki syndrome, who showed distinctive facial appearance and congenital heart disease (39). H3K9 methyltransferases, G9a and GLP, have been shown to be essential for cardiac morphogenesis (40). It is of note that the balance between methylation and demethylation of H3 is required for normal cardiac differentiation. *De novo* mutations in *SMAD2*, a transcription factor which regulates H3K27 methylation in embryonic left–right organizer, have been identified in children with congenital heart disease (28). *SMAD2*, which is regulated by ERK (41), has been found to bind to H3K27 demethylase JMJD3, and regulate H3K27 methylation

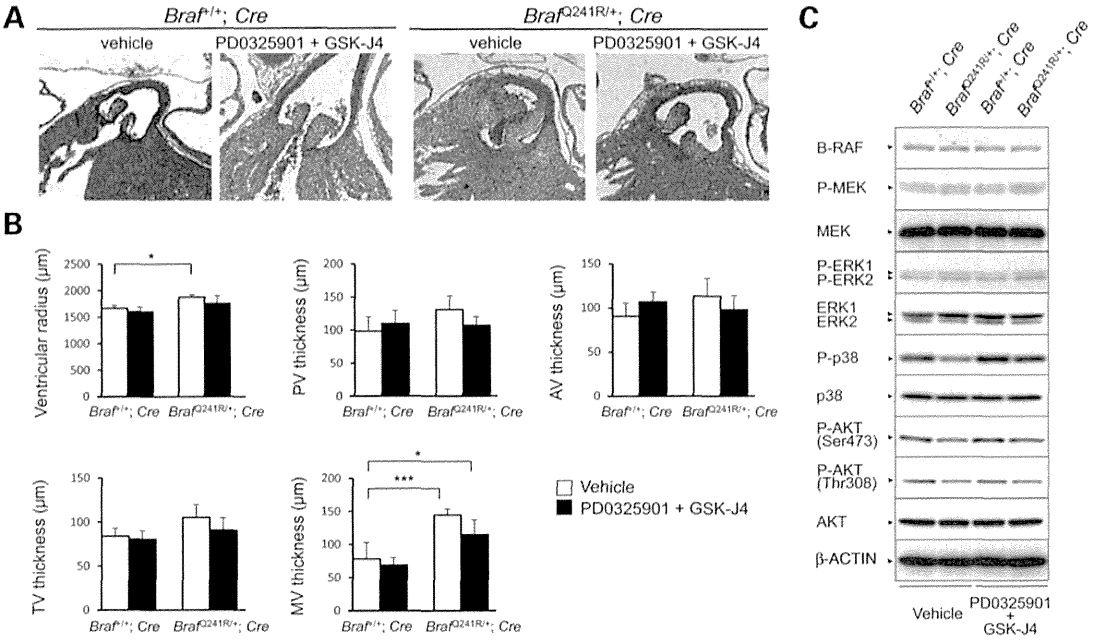

Figure 6. Influence of co-treatment with PD0325901 and GSK-J4 on the cardiac phenotype and signaling of *Braf*$^{Q241R/+}$; *Cre* embryos. (**A** and **B**) Sequential sections of embryonic hearts from *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* at E16.5 stained H&E. (A) Histological sections of pulmonary valves. (B) The ventricular radius and the thicknesses of the cardiac valve leaflets were measured at their largest diameter in serial sections. Data are means ± SD (vehicle; *Braf*$^{+/+}$; *Cre* ($n = 5$), *Braf*$^{Q241R/+}$; *Cre* ($n = 5$). PD0325901 + GSK-J4; *Braf*$^{+/+}$; *Cre* ($n = 7$), *Braf*$^{Q241R/+}$; *Cre* ($n = 11$)). $^{*}P < 0.05$, $^{***}P < 0.001$ (Tukey–Kramer test). NS, not significant. (**C**) Western blotting of the hearts from *Braf*$^{+/+}$; *Cre* and *Braf*$^{Q241R/+}$; *Cre* embryos at E16.5 (vehicle-treated pooled samples; *Braf*$^{+/+}$; *Cre* ($n = 8$), *Braf*$^{Q241R/+}$; *Cre* ($n = 8$). PD0325901 + GSK-J4-treated pooled samples; *Braf*$^{+/+}$; *Cre* ($n = 8$), *Braf*$^{Q241R/+}$; *Cre* ($n = 7$)). β-Actin is shown as a loading control. The arrowheads indicate the bands corresponding to each protein.

(28), suggesting that the histone demethylase JMJD3 is associated with heart development in humans by indirect regulation of ERK. In addition, constitutively activated BRAF and RAS mutants, through ERK activation, have been shown to induce JMJD3 and EZH2 expression (42,43). These observations suggest that activation of BRAF or ERK is associated with histone H3K27 modification, regulating cardiac development. In this study, the total content of the H3K27me3 in heart tissues of *Braf*$^{Q241R/+}$; *Cre* or *Braf*$^{Q241R/+}$; *Cre* mice after GSK-J4 co-treatment with PD0325901 was comparable with that of *Braf*$^{+/+}$; *Cre* mice (data not shown). Furthermore, the histone H3K27 demethylase activity of lysates from *Braf*$^{Q241R/+}$; *Cre* embryos at E14.5 was comparable with that of *Braf*$^{+/+}$; *Cre* (data not shown). Further analysis of H3K9 and H3K27 modification status on individual genes will clarify the mechanism by which histone demethylase inhibitor is effective against embryonic and postnatal lethality and developmental defects in *Braf*$^{Q241R/+}$; *Cre* mice.

MEK inhibitor treatment or crossing with ERK1 knockout mice has improved the hypertrophy of cardiac valves in Noonan syndrome model mice with a *SOS1* or *PTPN11* mutation (24,44). In contrast, treatment of MEK inhibitor did not lead to the amelioration of enlarged cardiac valves in *Braf*$^{Q241R/+}$; *Cre* embryos. Furthermore, other mice, excluding *Braf*$^{Q241R/+}$; *Cre*, treated with MEK inhibitor showed enlarged cardiac valves (data not shown), suggesting that the vital nature of MEK/ERK signaling balance in cardiac valve development. Given that no MEK inhibitor activity nor the inhibition activity of other protein kinases has been reported in GSK-J1 (GSK-J4 sodium salt) (25), these results suggest that not only MEK/ERK signaling balance but also histone H3K27 modification can play a crucial role in the normal development of cardiac valve in *Braf*$^{Q241R/+}$; *Cre* embryos.

The natural history and the frequency of tumors in adult CFC patients have not been fully elucidated (6). Since molecular analysis became available, three individuals with *BRAF* mutation have been reported to have developed acute lymphoblastic leukemia and non-Hodgkin lymphoma (6). Knockin mice expressing *BRAF* L597V mutation survived to adulthood and showed multiple Noonan syndrome/CFC syndrome phenotypes, including short stature, facial dysmorphia and cardiac enlargement (12). The L597V is located in the CR3 kinase domain and leads to 2-fold elevated BRAF kinase activity (45). The L597V mutation has been identified in 11 somatic cancers (COSMIC; http://cancer.sanger.ac.uk/cancergenome/projects/cosmic/) and three patients with Noonan syndrome (13,46,47), which generally shows milder phenotype than that in CFC syndrome. In contrast, Q257R mutation is located in the CR1 domain and has been identified in 40% of CFC syndrome, not in cancers. Our ELK transactivation study has shown that level of ELK transactivation in Q257R was a half of V600E (3). The previous report showed that BRAF Q257R has increased BRAF kinase activity compared with WT and the activity was as high as that of the V600E (4). It is possible that differences in kinase activity and/or the effect on downstream pathways could cause the phenotypic differences in these knockin mice. Surviving *Braf*$^{Q241R/+}$; *Cre* mice in the PD0325901 treatment showed distinctive facial appearance, abnormal dental occlusion, reduced postnatal length and weight, kyphosis and skin

disease, which are similar to CFC syndrome phenotype (data not shown) (1,48). *Braf*$^{Q241R/+}$; *Cre* mice also survived to adulthood when these mice (C57BL/6J background) were crossed with ICR or BALB/c mice (unpublished data). Further studies will be necessary to examine if adult *Braf*$^{Q241R/+}$; *Cre* mice show phenotypes similar to patients with CFC syndrome, including seizures and tumor development.

The potential mechanism of activation and downregulation of multiple signaling pathways in *Braf*$^{Q241R/+}$; *Cre* embryos is unclear. In additional studies, we performed microarray analysis and quantitative real-time PCR using heart tissues from *Braf*$^{Q241R/+}$; *Cre* embryos at E13.5 or E16.5. Interestingly, mRNA levels of dual specificity phosphatase (*Dusp*) 2, 4 and 6, that inactivate ERK, p38 or JNK, and *Spry* 1, which inhibits the RAS–MAPK signaling pathway, were significantly higher in *Braf*$^{Q241R/+}$; *Cre* embryos than those in *Braf*$^{+/+}$; *Cre* (data not shown). In the present study, constitutive activation of phosphorylated ERK was not clearly observed in whole embryos and heart tissues from *Braf*$^{Q241R/+}$; *Cre.* These results suggest that increased mRNA levels of *Dusp* 2, 4, 6 and *Spry* 1 and decreased expression of phosphorylated p38 in embryonic heart could represent a negative feedback mechanism for normalizing constitutive ERK activation in *Braf*$^{Q241R/+}$; *Cre* embryos.

In summary, *Braf* Q241R-expressing mice provided an effective tool for studying the pathogenesis of CFC syndrome. It was found for the first time that combination treatment with PD0325901 and GSK-J4 is efficacious for the treatment of mice with the activation of the RAS–MAPK pathway. At present, clinical trials of a new MEK inhibitor, MEK162, are now being conducted to investigate the efficacy and safety of its use in Noonan syndrome with hypertrophic cardiomyopathy as well as in individuals with solid tumors, while no clinical trial of histone H3K27 demethylase inhibitor has been performed. Given that *BRAF* mutations cause cancer, combination therapy with MEK inhibitors and histone H3K27 demethylase inhibitors can be effective not only for the treatment of patients with RASopathies but also for the treatment of *BRAF* mutation-associated cancer in the future.

MATERIALS AND METHODS

Generation of *Braf*^{Q241R} knockin mice

To construct the targeting vector for *Braf*^{Q241R} knockin mice, a short arm containing *Braf* exon 5 and 6 (*Not*I-*Sac*II genomic DNA fragment), a long arm including exon 7, 8 (*Xma*I–*Bam*HI genomic DNA fragment) and the downstream of exon 8 (*Bam*HI–*SacI*) were amplified using a Roswell Park Cancer Institute-23 BAC clone. The DNA fragments were ligated into the pBSIISK+ vector. The *Braf* Q241R (exon 7) mutation was introduced by site-directed mutagenesis. The *Psp*0MI–*Xho*I site was used to insert PGK-Neo-STOP cassette flanked by loxP sites. The targeting vector was linearized with *Sal*I and electroporated into ES cells (C57BL/6J background). To confirm correctly targeted ES clones, we performed genotyping, sequencing and the test of the Cre-mediated recombination system. Furthermore, homologous recombinants were confirmed by Southern blotting using 5′, 3′ and Neo probes. For this experiment, genomic DNA was digested with *Sac*I (5′ probe), *Nco*I (3′ probe) or *Afl*II (Neo probe). The probe sequences are shown in Supplementary Material, Table S5. Screened ES clones were then microinjected into BALB/c blastocytes and the resulting chimeras were crossed with C57BL/6J mice to obtain *Braf*$^{Q241R\ Neo/+}$ heterozygotes mice. Excisions of the PGK-Neo cassette and STOP codon were achieved by crossing of *Braf*$^{Q241R\ Neo/+}$ heterozygotes with CAG-Cre transgenic mice (*Braf*$^{+/+}$; *Cre*) on C57BL/6J background (RIKEN BioResource Center, Tsukuba, Japan; RBRC01828) (49). Animal experiments were approved by the Animal Care and Use Committee of Tohoku University.

Genotyping

Genomic DNA was prepared from tail tissue with DNeasy Blood & Tissue Kit (Qiagen, Hilden, Germany) or Maxwell 16 Mouse Tail DNA Purification Kit (Promega, Madison, WI, USA). Genotyping of the *Braf*$^{+/+}$, *Braf*$^{+/+}$; *Cre*, *Braf*$^{Q241R\ Neo/+}$ and *Braf*$^{Q241R/+}$; *Cre* was carried out by PCR using KOD FX Neo (TOYOBO, Osaka, Japan) or TaKaRa Taq (Takara Bio, Otsu, Japan) with the primers shown in Supplementary Material, Table S6.

Sequencing

Total RNA was extracted with TRIzol reagent (Invitrogen, Carlsland, CA, USA), and cDNA was synthesized using High-Capacity cDNA Reverse Transcription Kit (Applied Biosystems, Foster City, CA, USA). The exonic region in *Braf* was amplified by PCR using TaKaRa Taq with the primers including M13 sequences: 5′-GTAAAACGACGGCCAGTGAAGTACT GGAGAATGTCCC-3′ and 5′-AGGAAACAGCTATGACCC CACATGTTTGACAACGGAAACCC-3′. The PCR products were purified with QIAquick Gel Extraction Kit (Qiagen, Tokyo, Japan) and sequenced on an ABI 3500xl automated DNA sequencer (Applied Biosystems).

Quantitative reverse transcription–PCR

Quantitative PCR was performed using FastStart Universal Probe Master (ROX) (Applied Biosystems) with StepOnePlus (Applied Biosystems). Amplification primers and hydrolysis probes were designed using Universal ProbeLibrary Assay Design Center (https://qpcr.probefinder.com/roche3.html).

Alcian Blue/Alizarin Red staining

After embryos were placed in water for a day, the skin and viscera were removed. The eviscerated embryos were then fixed in 95% ethanol for at least 3 days and stained with 150 mg/l Alcian Blue 8GX (Sigma-Aldrich, St Louis, MO, USA), 80% ethanol and 20% acetic acid for 16–24 h. The stained embryos were rinsed with 95% ethanol and kept in 2% KOH for 16–24 h. They were then stained with 50 mg/l Alizarin Red (Sigma-Aldrich) and 1% KOH for 3 h, kept in 2% KOH for 12–48 h, placed in 20% glycerin/1% KOH for at least 5 days and stored in 50% glycerin.

Plasmid construction

The expression construct, including mouse *Braf* cDNA, was purchased from Origene (Rockville, MD, USA). PCR was performed using primers designed to introduce *Hin*dIII sites and the V5 epitope (C terminus). The PCR fragment was subcloned into pCR4-TOPO Vector (Invitrogen). The entire cDNA was verified by sequencing. The mutant constructs for *Braf* Q241R and V637E were generated using QuikChange Lightning Site-Directed Mutagenesis Kit (Stratagene, La Jolla, CA, USA) with the primers, 5′-CCGAAAGCTGCTTTTCCGGGGTTT CCGTTGTCAAA-3′ and 5′-TTTGACAACGGAAACCCCGG AAAAGCAGCTTTCGG-3′, and 5′-CTTTGGTCTAGCCACA GAGAAATCTCGGTGGAGTG-3′ and 5′-CACTCCACCGA GATTTCTCTGTGGCTAGACCAAAG-3′, respectively. All mutant constructs were verified by sequencing. The cDNAs were digested with *Hin*dIII, blunt-ended with T4 DNA polymerase and ligated into blunt-ended *Eco*RI site of pCAGGS vector (50).

Reporter assay

NIH 3T3 cells (ATCC, Rockville, MD, USA) were maintained in Dulbecco's modified Eagle's medium supplemented with 10% newborn calf serum, 50 U/ml penicillin and 50 μg/ml of streptomycin. The cells were seeded in 24-well plates at 3×10^5 cells/well 24 h before transfection. The cells were then transiently transfected using Lipofectamine and PLUS Reagent (Invitrogen) with 400 ng of pFR-luc, 25 ng of pFA2-Elk1, 5 ng of phRLnull-luc and 5 ng of WT or mutant expression constructs of *Braf*. Forty-eight hours after transfection, the cells were harvested in passive lysis buffer, and luciferase activity was assayed using Dual-Luciferase Reporter Assay System (Promega). Renilla luciferase expressed by phRLnull-luc was used to normalize the transfection efficiency.

Western blotting and phospho-kinase-antibody array

Whole-mouse embryos and brain were lysed in lysis buffer (10 mM Tris–HCl, pH 8.0 and 1% SDS), or genotype-confirmed hearts were pooled and lysed in the same buffer. These lysates were centrifuged at 14 000*g* for 15 min at 4°C and the protein concentration was determined by the Bradford method with Bio-Rad Protein Assay (Bio-Rad Laboratories, Hercules, CA, USA). Lysates were subjected to SDS–polyacrylamide gel electrophoresis (5–20% gradient gel; ATTO, Tokyo, Japan) and transferred to nitrocellulose membrane. Antibodies used were as follows (with catalog numbers in parentheses): B-RAF (9434), ERK1/2 (9102), phospho-ERK1/2 (9101), phospho-MEK (9121), p38 (9212), phospho-p38 (4511), phospho-SAPK/JNK (4668), AKT (9272), phospho-AKT (on Ser473; 9018) and phospho-AKT (on Thr308; 2965) from Cell Signaling (Danvers, MA, USA). C-RAF (610152), MEK (sc-219) and β-actin (A5316) were from BD Transduction Laboratories (San Jose, CA, USA), Santa Cruz Biotechnology (Santa Cruz, CA, USA) and Sigma-Aldrich, respectively. All the membranes were visualized using Western Lightning ECL-Plus Kit (Perkin-Elmer, Waltham, MA, USA). The band intensities were quantified using ImageJ software (http://rsbweb.nih.gov/ij/) and normalized to β-actin. Phosphorylated protein was measured to determine the ratios of phosphorylated protein to non-phosphorylated protein and then normalized to β-actin.

For kinase-antibody arrays, protein extracts of embryonic hearts (400 μg) were incubated with the Phospho-Kinase Antibody Array Kit (Proteome Profiler Antibody Array; R&D systems, Minneapolis, MN, USA) following the manufacturer's instructions.

Histology and immunohistochemistry

Embryonic hearts were perfused with phosphate-buffered saline and 10% neutral buffered formalin from the placenta. The fixed hearts and whole-mouse embryos fixed in 10% neutral buffered formalin were embedded in paraffin. Embedded tissues were sectioned at 6 μm (hearts) or 3 μm (whole-mouse embryos and lungs). Sections were stained with hematoxylin and eosin. In hearts from embryos at E16.5, the largest diameters of the ventricular radius were measured in serial coronal sections where a four-chamber view was observed. The largest thicknesses of cardiac valve leaflets in serial sections were measured. Edematous and dead embryos were excluded from these analyses.

For immunohistochemistry, the antibodies used were as follows (with catalog numbers in parentheses): phospho-Histone H3 (9701) from Cell Signaling, LYVE-1 (103-PA50AG) from RELIA Tech GmbH (Braunschweig, Germany), α-SMA (M0851) from DAKO (Glostrup, Denmark), PECAM-1 (CD31; sc-1506) from Santa Cruz Biotechnology and TTF-1 (MS-669-P1ABX) from Thermo Fisher Scientific (Fremont, CA, USA). Signals were amplified by Histofine Simple Stain (Nichirei Bio Sciences, Tokyo, Japan) and color was developed by DAB Substrate Kit (Nichirei Bio Sciences). Sections were counterstained with hematoxylin.

PAS staining

Deparaffinized lung sections were incubated in 0.5% periodic acid for 10 min at 60°C, rinsed with distilled water and stained in Schiff's reagent (Muto Pure Chemicals, Tokyo, Japan) for 10 min. Stained slides were counterstained with hematoxylin, dehydrated and mounted.

Animal treatment

Stock solution of PD0325901 (Sigma-Aldrich) was prepared using ethanol, whereas those of MAZ-51 (Calbiochem, San Diego, CA, USA), Sorafenib (Toronto Research Chemicals, North York, ON, USA), Lovastatin (Calbiochem), Everolimus (Selleckchem, Houston, TX, USA), NCDM-32b (Wako Pure Chemicals, Osaka, Japan), GSK-J4 (Cayman Chemical) and the combination of PD0325901 and GSK-J4 were prepared using dimethylsulfoxide. PD0325901 was resuspended in saline while and all other reagents were resuspended in 0.5% hydroxypropylmethylcellulose with 0.2% Tween80, respectively. The prepared reagents or vehicles were i.p. injected into pregnant mice daily, beginning on E10.5 and continuing till E15.5 or E18.5.

Statistical analysis

All statistical analysis was performed using Prism software (ver. 6.01; GraphPad Software, Inc., San Diego, CA, USA). Data analysis were performed with Student's *t*-test for unpaired samples, one-way analysis of variance followed by the Tukey–Kramer test for comparison of multiple experimental groups and the χ^2 test for differences between observed and expected distributions. Differences were considered significant at a *P*-value of < 0.05.

SUPPLEMENTARY MATERIAL

Supplementary Material is available at *HMG* online.

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Conflict of Interest statement. None declared.

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