Rudhira-mediated microtubule stability controls TGFβ signaling during mouse vascular development.

Divyesh Joshi[1#], Preeti Jindal[1#], Ronak Shetty[1] and Maneesha S. Inamdar[1,2*]

[1]Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India;. [2]Institute for Stem Cell Science and Regenerative Medicine (inStem), Bangalore, India.

# Equal contribution

*Author for correspondence

Email: inamdar@jncasr.ac.in

Tel: +91-080-2208-2818

ORCID: 0000-0002-8243-2821

Running title: Rudhira bridges microtubule stability and TGFβ signaling.

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Abstract

The Transforming Growth Factor β (TGFβ) signaling pathway is critical for survival, proliferation, and cell migration, and is tightly regulated during cardiovascular development. Smads, key effectors of TGFβ signaling, are sequestered by microtubules (MTs) and need to be released for pathway function. Independently, TGFβ signaling also stabilizes MTs. Molecular details and the *in vivo* relevance of this cross-regulation remain unclear, understanding which is important in complex biological processes such as cardiovascular development. Here, we use *rudhira/Breast Carcinoma Amplified Sequence 3 (BCAS3)*, a MT-associated, endothelium-restricted and developmentally essential proto-oncogene, as a pivot to decipher cellular mechanisms in bridging TGFβ signaling and MT stability. We show that Rudhira regulates TGFβ signaling *in vivo,* during mouse cardiovascular development, and in endothelial cells in culture. Rudhira associates with MTs and is essential for the activation and release of Smad2/3 from MTs. Consequently, Rudhira depletion attenuates Smad2/3-dependent TGFβ signaling thereby impairing cell migration. Interestingly, Rudhira is also a transcriptional target of Smad2/3-dependent TGFβ signaling essential for TGFβ-induced MT stability. Our study identifies an immediate early physical role and a slower, transcription-dependent role for Rudhira in cytoskeleton- TGFβ signaling crosstalk. These two phases of control could facilitate temporally- and spatially restricted targeting of the cytoskeleton and/or TGFβ signaling in vascular development and disease.

43 **Significance statement**

44 The developmental TGFβ pathway is essential for cell migration, cell-cell communication, adhesion,
45 apoptosis, and matrix remodeling. Dysregulation of TGFβ signaling leads to aberrant vascular
46 patterning and angiogenesis during mouse embryogenesis. Pathway activation involves
47 phosphorylation and nuclear transport of Smads. Microtubules sequester Smads in the cytoplasm,
48 thereby inhibiting TGFβ signaling. Conversely, TGFβ signaling stabilizes microtubules. However, the
49 molecular components involved, and biological relevance of this cross-regulation remain unclear. We
50 show that the oncoprotein Rudhira/BCAS3 facilitates Smad-MT dissociation upon ligand-mediated
51 TGFβ receptor activation. Interestingly, Smad-dependent TGFβ signaling activation enhances rudhira
52 transcription, essential for microtubule stabilization during cardiovascular development. This dual
53 regulation of TGFβ signaling and microtubule stability by Rudhira allows sustained temporal control
54 essential for development, and its dysregulation has pathological outcomes.

55

56

57 **Introduction**

58

59 Cytoskeletal organization and growth factor signaling are mutually dependent and coordinate
60 multiple cellular processes [1]. The multifunctional Transforming growth factor β (TGFβ) pathway
61 regulates cell proliferation, differentiation, survival and migration and is sensitive to cytoskeletal
62 rearrangements [1-3]. Depletion of TGFβ pathway components causes developmental
63 abnormalities often leading to embryonic death [4]. Ligand binding activates the TGFβ receptor,
64 causing receptor-mediated phosphorylation, followed by nuclear translocation of Smad
65 proteins, resulting in transcriptional regulation of target gene expression [5]. Smads, the effectors
66 of the TGFβ pathway, are competitively bound by several proteins and are a hub for regulation
67 of TGFβ signaling and its intersecting pathways [6]. MTs bind to and sequester Smad2/3 and
68 Smad4, thereby negatively regulating TGFβ signaling, which is relieved upon TGFβ stimulation
69 [7]. Conversely, TGFβ signaling stabilizes MTs [8, 9] through an as yet unclear mechanism,
70 suggestive of a feedback loop.

71

72 During development, TGFβ signaling is activated in endothelial cells (ECs) of the remodeling
73 angiogenic endothelium and is critical for vascular development [10]. MT stability is also essential
74 for angiogenic sprouting in ECs [11]. MTs can be stabilized in multiple ways within the cell, initially
75 by RhoA-mDia actin bundling and thereafter by interaction with multi-protein complexes. Serum
76 components, TGFβ and Lysophosphatidic acid (LPA), have been shown to stabilize MTs [8, 12].
77 While LPA stabilizes MTs within 30 min post-stimulation and generically [12], the effect of TGFβ
78 signaling takes at least 2 hours [8] but is more restricted to and essential for endothelial cell
79 function *in vivo*. Slow and restricted induction of MT stability by TGFβ as compared to the more
80 generic and rapid function of LPA suggests a requirement for new transcription/translation which
81 may be developmentally important. However, the molecular mechanisms and biological
82 relevance of cytoskeletal interactions with TGFβ signaling remain elusive. Characterization of
83 tissue-restricted regulators of the ubiquitous MT cytoskeleton may aid in defining its specialized
84 context- dependent functions.

85

86 In this study, we address the role of the MT-interacting protein Rudhira in connecting TGFβ signaling
87 and MT stability. Rudhira associates with MTs and intermediate filaments (IFs), stabilizes MTs and

promotes directional cell migration [11, 13]. *Rudhira* knockout in mouse causes mid-gestation lethality due to aberrant cardiovascular patterning [14]. Transcriptome analysis showed that several processes were deregulated in the *rudhira* knockout, especially, a large number of TGFβ signaling pathway components [14]. This suggests that Rudhira may regulate TGFβ signaling for vascular development.

Here, we show that Rudhira-depleted cells have reduced Smad2/3 activation during mouse embryonic development, indicating that Rudhira is a positive regulator of TGFβ signaling. We demonstrate that Rudhira facilitates TGFβ-mediated release of Smad2/3 from MTs. Further, TGFβ signaling stabilizes MTs by inducing transcription, in a Rudhira-dependent manner. Thus, Rudhira bridges TGFβ signaling and MT stability, required for cardiovascular development. Ectopic and aberrant Rudhira expression is seen in several carcinomas and positively correlates with tumor metastatic potential [15-17]. Hence our study will aid understanding of TGFβ signaling and suggest novel ways to regulate it in development and disease.

Results

Rudhira depletion attenuates Smad2/3-dependent TGFβ signaling *in vivo* and *in vitro*

Rudhira is an essential gene, critical for mouse cardio-vascular development [14]. Ubiquitous (*rudh*$^{-/-}$) or endothelial (*rudh*^{CKO}) knockout of *rudhira* results in angiogenic defects and mid-gestation embryonic lethality [14]. Transcripts of several components of the TGFβ pathway are deregulated upon Rudhira depletion and the knockout phenocopies mutants of several TGFβ pathway components, whose primary phenotype is in the cardiovascular system [10]. Hence, we characterized the role of Rudhira in TGFβ signaling. Analysis of the molecular interaction, reaction and relation networks by KEGG pathway mapping indicated that multiple components of the TGFβ pathway were deregulated in the absence of Rudhira, affecting several processes important for cardiovascular development (Fig. 1A). To validate this, we used non-silencing (NS) control and rudhira knockdown (KD) saphenous vein endothelial cell lines (SVEC) as described before (Fig S1A, B) [14]. To test the pathway regulation at the level of receptors, we analysed transcript and basal as well as active protein levels. While we observed some reduction in transcript levels of

119 *tgfbrI* and *tgfbrII* (Fig. S2A), the basal and active protein levels of TGFβRI remained unchanged in
120 KD cells (Fig. S2B). Interestingly, a constitutively active form of TGFβRI (TGFβRIT204D), expressed
121 under the CMV promoter, was also suppressed in Rudhira KD (overexpression achieved in NS ~200
122 folds while in KD ~80 folds) (Fig. S2C). TGFBR1 protein has a short half-life, while the mRNA is
123 relatively stable [18]. Reduced amount of relatively stable RNA may be sufficient to produce
124 adequate protein levels. These increased levels of active TGFβRI in KD were unable to restore
125 Smad2 phosphorylation, unlike NS controls, which showed a clear increase (Fig. 1B). While
126 important to note that Rudhira or its loss may regulate *tgfbr* transcript levels, these results support
127 a receptor-independent role of Rudhira in regulating TGFβ pathway.
128
129 To probe further into the molecular mechanism by which Rudhira controls TGFβ signaling, we used
130 *rudhira* knockout mice and the KD endothelial cell line. Upon TGFβ-stimulation ECs in culture showed
131 reduced Smad2 activation in the KD as compared to NS control (Fig. 1C). Further, qRT-PCR analysis
132 showed that transcript levels of Smad2/3 targets, namely *mmp9* and *pai1*, did not increase
133 significantly in KD, whereas NS control showed >2-fold increase for both (Fig. 1D). Expectedly, partial
134 restoration of Rudhira level in KD cells restored Smad2 activation and target gene expression (Fig.
135 1C, D). The canonical TGFβ pathway also responds to BMP4 activation. However, upon stimulation
136 with BMP4 there was no significant difference in the levels of pSmad1/5/8 between NS and KD (Fig.
137 S2D). These data indicate that Rudhira is required for TGFβ-dependent Smad2 phosphorylation and
138 pathway activation.
139
140 Endothelial depletion of Rudhira (*rudh*^{CKO}) is sufficient to cause vascular defects [14] and functional
141 TGFβ signaling is essential for vascular development [19]. Expectedly, *rudh*^{CKO} embryos showed a
142 concomitant loss of pSmad2/3 in the embryonic endocardium (Fig. 1E, E'), without affecting the
143 total Smad2/3 level (Fig. S2E, E'). Thus, Rudhira regulates TGFβ signaling in a Smad2/3-dependent
144 manner *in vivo*, which is essential for angiogenesis and endothelial cell migration during cardio-
145 vascular development.
146
147 **Rudhira is required for TGFβ mediated cell migration**
148 As Rudhira is essential for cell migration, we tested the effect of altered TGFβ pathway activity in
149 Rudhira KD endothelial cells (SVEC) in a transwell migration assay. We also validated our results in
150 HEK293 cells as these allow a high efficiency of transfection and Rudhira overexpression, for

151 migration assays. TGFβ addition did not enhance migration in *rudhira* knockdown (KD) cells as
152 compared to controls (NS and rescued KD) (Fig. 2A). In addition, ectopic Rudhira expression in
153 HEK293 cells caused increase in migration rate as compared to the control, consistent with our
154 earlier study [13] (Fig. 2B,C).
155
156 TGFβ supplementation of Rudhira overexpressing cells dramatically enhanced the rate of cell
157 migration (~2.6 fold), suggesting a direct correlation between Rudhira levels and pathway
158 function (Fig. 1C, D). Serum contains TGFβ in a concentration range of 10-40 ng/ml [20] and
159 we used 5% FBS with or without additional TGFβ in the transwell migration assay, since purified
160 TGFβ alone is unable to induce migration. The ratio of increase in migration rates with or without
161 exogenous TGFβ addition was similar in both the control and Rudhira-overexpressing cells (~1.5
162 fold). Interestingly, TGFβ pathway-inhibition by SB431542 (SB) restored the effect of Rudhira
163 overexpression (enhancement in cell migration rate) to control levels (Fig. 2B, S3A) suggesting
164 that Rudhira function is regulated by the TGFβ pathway downstream of receptor activation. In
165 addition to the multiple molecular pathways that function in concert to control cell migration [21],
166 our data support a role for Rudhira in TGFβ-dependent cell migration.
167
168 **Rudhira regulates TGFβ signaling by promoting the release of Smad2/3 from MTs**
169 Since Rudhira localizes to the cytoskeletal components, namely microtubules and intermediate
170 filaments [13], we hypothesized that it regulates TGFβ signaling at the cytoskeleton. However, we
171 could not detect any interaction between Rudhira and Smad2/3 under the conditions tested (Fig.
172 3A), suggesting that the effect on the pathway may be indirect, possibly through MTs. TGFβ
173 signaling is controlled at multiple levels, including cytoskeletal regulation at MTs, which interact
174 with and sequester Smad2/3 thereby inhibiting the TGFβ pathway [7]. TGFβ stimulation releases
175 Smads from MT sequestration in multiple cell types including endothelial cells, facilitating its
176 activation and nuclear translocation [7]. Expectedly, TGFβ stimulation in ECs (confirmed by increase
177 in pSmad2 levels) reduced Smad-MT binding as seen by co-immunoprecipitation for β-Tubulin
178 and immunoblotting for Smad2 (Fig. 3B).
179
180 To assess whether Rudhira is required for TGFβ-dependent release of Smad from MTs, we tested
181 for β-Tubulin and Smad interaction upon TGFβ stimulation in NS and KD cells by performing *in situ*
182 Proximity Ligation assay (PLA) [22]. While NS cells showed reduced Smad-MT interaction, KD cells

183 retained Smad-MT interaction even upon TGFβ stimulation in multiple KD cell lines (Fig. 3C, Fig. S3B).
184 Interestingly, TGFβ stimulation resulted in an increase in Rudhira-MT association in wild type
185 cells, detected by colocalization (Fig. 3D) and confirmed by PLA (Fig. 3E). Thus TGFβ-stimulated
186 Rudhira-MT association makes MTs unavailable for Smad binding. However, MTs are abundant and
187 present as subsets, differing in their Tubulin isotype and isoform composition, post translational
188 modifications (PTMs) and stability [23], which may also govern their interactions with other
189 molecules. It is unlikely that Rudhira binds to all MTs present. Also, it is likely that only a subset of
190 MTs may bind and sequester Smads.
191

192 ***Rudhira* is a transcriptional target of TGFβ signaling and is essential for MT stability**

193 The TGFβ pathway is auto-regulatory, due to which several pathway components are induced
194 or inhibited [24, 25]. The *rudhira* promoter harbors putative Smad-binding elements (SBEs) (Fig. S4A).
195 It also harbors putative binding sites of major TGFβ pathway regulated transcription factors (TFBS)
196 (Fig. S4B, Table S2). Expectedly, TGFβ stimulation increased *rudhira* mRNA and protein levels (Fig.
197 4A, B, C). Knockdown of *smad2* or *smad3* resulted in significant reduction of Rudhira levels,
198 indicating that *rudhira* is a Smad2/3-dependent TGFβ target (Fig. 4D). Blocking transcription
199 with Actinomycin D (AcD) or translation using Cycloheximide (CHX) prevented increase in *rudhira*
200 levels upon TGFβ stimulation, confirming that *rudhira* is a transcriptional target of the Smad2/3-
201 dependent TGFβ pathway (Fig. 5A, S4C). However, additional investigation is required to confirm
202 whether *rudhira* is a direct target of Smad2/3-dependent TGFβ pathway.
203

204 Rudhira and TGFβ signaling, both can induce MT stabilization [8, 11]. Although the mechanism
205 is unclear, PTMs and/or transcription may control TGFβ-induced MT stability [8]. Since *in vivo*
206 studies indicated that *rudhira* deletion severely affects the TGFβ pathway [14], we tested whether
207 TGFβ- induced transcription is required for MT stability. TGFβ stimulation results in a slow
208 enhancement of MT stability over a period of several hours, allowing sufficient time for
209 transcriptional regulation [8]. Interestingly, we find that blocking transcription or translation,
210 prevented TGFβ-dependent MT stabilization, as detected by Glu-tubulin levels (Fig. 5A, S4C),
211 correlating well with Rudhira levels and validated by increased sensitivity to Nocodazole-mediated
212 MT depolymerization (Fig. 5B). These data show that TGFβ induced MT stability is transcription-
213 dependent.
214

215 **TGFβ signaling stabilizes MTs in a Rudhira-dependent manner**

216 Since *rudhira* transcription is dependent on TGFβ signaling and Rudhira is required for MT stability,
217 we further tested whether TGFβ-induced MT stability is Rudhira-dependent. Serum starvation
218 resulted in low detectable levels of Glu-tubulin in NS and KD cells (Fig. 5C). Stimulation with
219 TGFβ or serum led to increased Glu-tubulin level in NS but not in KD cells showing that TGFβ-
220 induced MT stability is dependent on Rudhira (Fig. 5C, D). To test whether Rudhira stabilizes MTs
221 *in vivo* also, we analyzed the effect of loss of Rudhira on MT stability in the developing
222 endocardium. Interestingly, along with reduced pSmads levels observed earlier (Fig. 1E, E'), we found
223 that Glu-tubulin positive stable MTs were fewer in *rudh*^{CKO} embryonic endocardium (Fig. 5D),
224 supporting a role of Rudhira in regulation of TGFβ signaling and MT stability during cardiovascular
225 development. Combined, our study suggests that Rudhira primarily affects MTs to modulate
226 their Smad-binding property and downstream TGFβ signaling. Consequently, Smad2/3-dependent
227 TGFβ signaling induces *rudhira* transcription leading to MT stabilization essential for cardiovascular
228 remodeling during development (Fig. 5E).

229

230

231

232 **Discussion**

233 Growth factor signaling and cytoskeletal remodeling are mutually dependent processes that
234 require complex context-dependent molecular crosstalk [1]. Specifically, the developmentally
235 essential, tissue-restricted TGFβ signaling pathway, regulates and is regulated by the MT
236 cytoskeleton. However, the underlying molecular mechanism and *in vivo* relevance of this cross-
237 regulation remain elusive. In this study, we probed the role of Rudhira in the cytoskeletal control
238 of TGFβ signaling and, in turn, its effect on MT properties. Our study identifies a dual role of
239 Rudhira during vascular development- an early role in MT-mediated regulation of Smad2/3
240 and a late role as a transcriptional target of TGFβ signaling required for MT stability.

241

242 While several processes important for cardiovascular development were deregulated in
243 *rudhira*$^{-/-}$ embryos, the TGFβ pathway was primarily affected [14]. TGFβ signaling is a complex
244 pathway and is regulated at multiple levels by various feedback loops. One of the complicated yet
245 delicate feedback circuits is the regulation of receptor levels and activity [25]. Rudhira depletion
246 reduces transcript level without altering basal and active protein level of TGFBRI. This disparity in the
247 transcript and protein level may arise from the fact that while the *tgfbr* transcript is very stable, the
248 protein is quite unstable, and lower transcript levels may still be sufficient for generating adequate
249 protein levels. Such a phenomenon is not unusual, particularly for membrane proteins, where mRNA
250 levels may not correlate with protein levels. Rudhira, in a manner not yet understood, may also be
251 a part of a broader feedback pathway as it further negatively regulates levels of TGFβ pathway
252 inhibitors such as Smurfs and Smad7 [14], suggesting that additional regulatory mechanisms may
253 operate.

254

255 TGFβ signaling and Rudhira promote cell migration in a synergistic and inter-dependent manner.
256 Mechanistically, Rudhira promotes TGFβ-dependent release of Smads from MTs likely due to
257 increased Rudhira-MT association. This could allow pathway activation and result in enhanced cell
258 migration. Additional, confounding factors downstream of the autoregulatory TGFβ pathway or
259 pathway targets, as described above, may also contribute to Rudhira dependent cell migration in
260 response to TGFβ. Converse regulation of Rudhira-MT and Smad-MT interaction is indicative of
261 probable competition between Smads and Rudhira for MT binding, which merits further
262 investigation. Binding of Rudhira to MTs may also alter them in a way that makes MTs unavailable
263 for Smad binding. Since TGFβ stimulation is known to stabilize microtubules, we hypothesize that

264 TGFβ stimulation increases Rudhira binding to stable microtubules. While unclear molecular events
265 involved in release of Smads from MTs, and MT stabilization by Rudhira make it difficult to assign
266 causal roles, this study supports the hypothesis that dissociation of Smads from MTs is essential for
267 Smad activation. In addition, though MTs are ubiquitously and abundantly present, our data
268 suggest that only a few MTs participate in Smad sequestration. This is in concordance to our
269 earlier study which shows that Rudhira associates preferentially with stable MTs [11].
270
271 The TGFβ signaling pathway is autoregulatory and many of its components are also targets of the
272 pathway [24]. The *rudhira* promoter harbors Smad Binding Elements (SBEs). We show that Rudhira,
273 in addition to being a regulator of the TGFβ pathway, is also a transcriptional target. However,
274 further analysis is required to identify the specific mechanisms by which Smad-dependent, TGFβ-
275 induced, *rudhira* transcription is regulated during development. In contrast to this positive feedback,
276 TGFβ pathway is also negatively self-regulated, allowing for return to basal state amenable for
277 reactivation. This self-suppression could possibly involve increased turnover of receptors and
278 Smad2/3, and increased expression of inhibitory Smads, that may recover responsiveness to TGFβ
279 stimulation. Additionally, in the context of MT-dependent Smad2/3 inhibition, the still short turnover
280 time of stable MTs (several minutes to hours) may also promote quick return to resting state. These
281 interesting possibilities can now be tested.
282
283 *Rudhira* expression is tightly regulated and restricted to the remodeling endothelium
284 during development [14]. Mechanistically, Rudhira promotes MT stability for angiogenic
285 remodeling [11]. Independent studies show that TGFβ signaling, and MT reorganization are
286 essential for cardiovascular development [26-28]. Deletion of *smad2/3* or *tubulins* leads to
287 embryonic lethality with severely defective embryonic and extra-embryonic vasculature [29].
288 However, the role of MT stability for angiogenic sprouting *in vivo* and the underlying molecular
289 mechanisms remain elusive. Our study suggests that endothelial cytoskeleton remodeling by
290 Rudhira and activation of TGFβ signaling during cardiovascular development are inter-dependent
291 and cross-regulated. TGFβ signaling may lead to restricted induction of MT stability by inducing
292 the expression of MT-stabilizing developmentally regulated proteins like Rudhira. Additional
293 cytoskeletal components such as Vimentin that interacts with Rudhira, and is also a target of TGFβ
294 signaling, are likely to be involved [11, 13]. Our analysis will help gain better insight into cellular
295 processes such as migration, which require maintenance of cytoskeletal stability and active

296 signaling for extended periods. An added advantage will be the ability to decipher deregulated
297 migration such as in tumor metastasis. While targeting MT-Smad interaction would allow
298 regulation of the TGFβ pathway, the ubiquitous nature of these molecules is likely to result
299 in widespread and possibly undesirable effects of therapeutic intervention. Rudhira expression,
300 being more restricted, could provide a suitable target to regulate developmental and pathological
301 TGFβ signaling.
302
303
304 **Materials and methods**
305
306 **Animal experiments**
307 Animal experiments were performed as mentioned earlier [14]. All animal experimental protocols
308 were approved by the Institutional Animal Ethics Committee (IAEC) of JNCASR (Project number
309 MSI006. All animals were maintained, and experiments were performed according to the guidelines
310 of the animal ethics committee of JNCASR. *Rudhira* floxed mice and conditional knockout mice (*Tek-*
311 *Cre* mediated endothelial deletion, $rudhira^{flox/flox}$; $TekCre^{+}$, abbreviated to $rudh^{CKO}$) were validated by
312 genotyping.
313
314 **Cell culture, transfections, and small molecule treatments**
315 Cell line sources and generation is reported elsewhere [14]. In brief, *rudhira* shRNA vectors (715,
316 716), and scrambled (non- silencing) control vector (TR30015) (Origene, USA) were microporated
317 into SVEC (mouse endothelial cell line) and selected for stable line generation. Control cell line is
318 referred to as 'NS' and *rudhira* knockdown as 'KD'. For Rudhira overexpression and rescue line, the
319 plasmid constructs used were GFP-2A-GFP and Rudh-2A-GFP which are described elsewhere [13].
320 Constitutively active TGFβRI (pcDNA3-ALK5 T204D, 80877) was purchased from addgene for
321 transfection of SVEC NS and KD cells. Control and shRNA vectors for s*mad2* or *smad3* knockdown)
322 were purchased from ShRNA Resource Centre (Department of Microbiology and Cell Biology, Indian
323 Institute of Science, Bangalore, India) and were from the SIGMA Library of shRNAs for Human gene
324 products. The shRNAs were transfected in HEK293T cells and selected in 1 µg/ml Puromycin for 7

325 days. Details of the oligonucleotide sequence of the shRNAs are provided in Supplementary Table S3.
326 HEK293, HEK293T cellswere transfected using Calcium Phosphate method while SVEC cells were
327 transfected using Lipofectamine 2000 (ThermoFisher Scientific, USA). All small molecules were from
328 Sigma Chemical Co., USA, and treatments were performed in DMEM, unless otherwise indicated.
329 Cells were washed three times in PBS and serum starved for 12h. Thereafter, cells were kept
330 untreated or treated with 10 ng/ml of TGFβ (Fig. 1C) or BMP4 (Fig. S2D) for 2 h and then taken for
331 immunoblotting. For gene expression analysis, cells were induced with 10 ng/ml of TGFβ for 24 to 48
332 h (Figs. 1D, 4A, B, C, S3C). SB431542 was used at a concentration of 10 µM, as indicated (Fig. 2A, B
333 and S3A). For Transwell migration assays, small molecule dilutions were prepared in 5% FBS
334 containing DMEM (Fig. 2A, B). For interaction studies cells were serum starved for 12h and thereafter
335 kept untreated or treated with 10 ng/ml of TGFβ or 10% FBS for 2 h and then taken for PLA,
336 immunostaining or western blotting, as desired (Fig. 3, S3A, B). For TGFβ-dependent *rudhira*
337 transcription and MT stability assays, cells were serum starved for 48h in serum-free medium (SFM)
338 containing 5 mg/ml BSA and 20mM HEPES (pH 7.4) in DMEM. Thereafter, various treatments were
339 performed for 7h (Fig. 5A, B, C, S4C, D). TGFβ (10 ng/ml), Actinomycin D (AcD, 10 µM), Cycloheximide
340 (50 µg/ml) were diluted in SFM.
341

342 **Quantitative RT-PCR (qRT-PCR)**

343 RNA was isolated using TRIzol reagent (Invitrogen). Reverse transcription was performed using 2 µg
344 of DNase treated RNA and Superscript II (Invitrogen, Carlsbad, CA) according to manufacturer's
345 instructions. Quantitative RT-PCR (qRT-PCR) was carried out using EvaGreen (BIO-RAD, CA) in Biorad-
346 CFX96 Thermal cycler (BIO-RAD, CA). Details of primers used are provided in Supplementary Table
347 S1.
348

349 **Immunostaining, Immunohistochemistry, Fluorescence Microscopy and Analysis**

350 Yolk sac or embryos dissected at E10.5 were fixed in 4% paraformaldehyde and processed for
351 Cryosectioning (embryos) and immunostaining using standard procedures. Control and knockout
352 embryos were identified by embryonic tail genotyping. Cells were fixed in 4% paraformaldehyde at
353 room temperature or 100% methanol at -20 ˚C and processed for immunostaining using standard
354 procedures [30]. Primary antibodies used were against PECAM1 (CD31) (BD Biosciences, USA),

355 Rudhira, Smad2/3, pSmad2, pSmad2/3 (Cell Signaling Technology), β-Tubulin (DSHB, Iowa), Glu-
356 Tubulin (Abcam), GFP (Invitrogen). Secondary antibodies were conjugated with Alexa-Fluor 488 or
357 Alexa-Fluor 568 or Alexa-Fluor 633 (Molecular Probes). Bright field and phase contrast microscopy
358 were performed using an inverted (IX70, Olympus) microscope. Confocal microscope, LSM 880 with
359 airy scan, Zeiss, was used for fluorescence microscopy. All images in a set were adjusted equally for
360 brightness and contrast using Adobe Photoshop CS2, where required.
361

362 **Immunoblot analysis and co-immunoprecipitation**

363 50 µg whole cell lysate was used for western blot analysis by standard protocols. Blots were cut into
364 strips and incubated with primary antibodies as indicated: Smad2/3, pSmad2, Smad1/5/8,
365 pSmad1/5/8 (Cell Signaling Technology), GAPDH (Sigma Chemical Co., USA), Glu-Tubulin, Ubiquitin,
366 TGFβRI, pTGFβRI (Abcam, USA), β- Tubulin (DSHB, Iowa), Rudhira (Bethyl Labs, USA). HRP conjugated
367 secondary antibodies against appropriate species were used and signal developed by using Clarity
368 Western ECL substrate (Biorad, USA). For co-immunoprecipitation, 500 µg whole cell lysate and 2 µg
369 of the desired antibody were used. Complexes were captured on Protein G-Agarose beads and
370 analyzed by immunoblotting.

371

372 **Transwell migration assay**

373 The assays and quantitation were carried out as mentioned earlier [13]. Briefly, 24 h after
374 transfection with desired plasmid vectors, cells were serum-starved for 12 h and 20000 HEK cells or
375 40000 SVEC were plated onto the upper chamber of the transwell filter inserts with 8 µm pore size,
376 24-well format (Costar, USA). 10% FBS containing medium (with desired small molecules) was added
377 to the lower chamber to serve as a chemo-attractant. After 24 h, cells were fixed in 4%
378 paraformaldehyde for 10 min at room temperature. Cells on the top of the filter were removed using
379 a cotton swab. Cells that had migrated to the bottom were fixed and stained with 0.5% crystal violet
380 for 10 min at room temperature. The dye was extractedin methanol and absorbance measured
381 spectrophotometrically at 570 nm.

382

383 ***In situ* Proximity Ligation Assay (PLA or Duolink assay)**

384 *In situ* PLA (Proximity Ligation Assay) reaction was performed on SVEC cell lines. The cells were
385 cultured, fixed, permeabilised and stained with primary antibodies for Smad2/3, β-Tubulin or
386 Rudhira, as desired. Thereafter, the protocol for PLA as recommended by manufacturer (Duolink,
387 USA) was followed. Post PLA, nuclei were counterstained with DAPI.

388

389 **Rudhira promoter *in silico* analysis**

390 Smad-binding elements or motifs (SBEs) and other transcription factor binding sites (TFBS) were

391 identified from experimental studies, available in JASPAR database (https://jaspar.genereg.net/).
392 PSCAN software (http://159.149.160.88/pscan) was used for motif scanning in mouse and human
393 *rudhira/BCAS3* gene promoters (1 kb sequence upstream of the transcription start site) using
394 matrices obtained from JASPAR bioinformatics tool, as indicated. (Supplementary Table S2).
395

396 **Quantification and Statistical analyses**

397 Statistical analyses were performed using One Way ANOVA in the Data Analysis package in Microsoft
398 Excel, and two-way ANOVA and one-sample t-test in GraphPad Prism. $p<0.05$ was considered
399 significant.
400

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412

413 **Author Contributions**

414 MSI conceived of the project and directed the work. DJ, PJ, RS, MSI performed and analyzed
415 all the experiments. DJ, PJ, MSI wrote the manuscript. Authors have no competing interests.

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417

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Figures

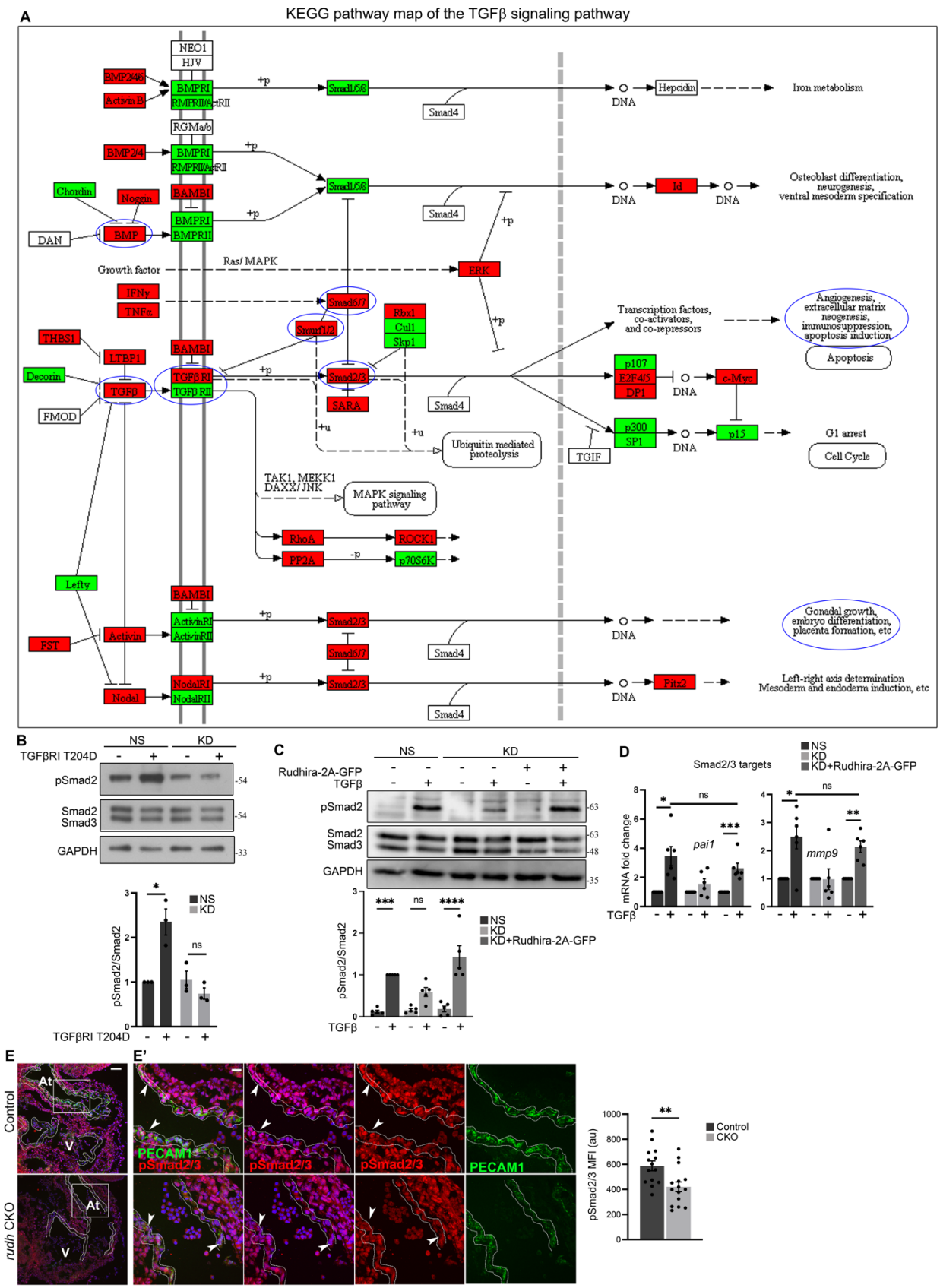
A
KEGG pathway map of the TGFβ signaling pathway
NEO1
HJV
BMP2/4/6
Activin B
BMPRI
RMPRII/A
tRII
RGMa/b
BMP2/4
BAMBI
Chordin
Noggin
DAN
BMP
BMPRII
Smad1/5/8
Smad4
DNA
Hepcidin
Iron metabolism
Id
Osteoblast differentiation, neurogenesis, ventral mesoderm specification
Growth factor
Ras/ MAPK
ERK
IFNγ
TNFα
Smad6/7
Smurf1/2
Rbx1
Cul1
Skp1
THBS1
LTBP1
Decorin
TGFβ
TGFβ RI
TGFβ RII
FMOD
Smad2/3
SARA
Transcription factors, co-activators, and co-repressors
Angiogenesis, extracellular matrix neogenesis, immunosuppression, apoptosis induction
Apoptosis
p107
E2F4/5
DP1
c-Myc
p300
SP1
p15
G1 arrest
Cell Cycle
TGIF
Ubiquitin mediated proteolysis
TAK1, MEKK1
DAXX/ JNK
MAPK signaling pathway
RhoA
ROCK1
PP2A
p70S6K
Lefty
FST
Activin
ActivinRI
ActivinRII
Gonadal growth, embryo differentiation, placenta formation, etc
Nodal
NodalRI
NodalRII
Pitx2
Left-right axis determination
Mesoderm and endoderm induction, etc
B
NS
KD
TGFβRI T204D
pSmad2
Smad2
Smad3
GAPDH
pSmad2/Smad2
C
Rudhira-2A-GFP
TGFβ
KD+Rudhira-2A-GFP
D
Smad2/3 targets
mRNA fold change
pai1
mmp9
E
E'
Control
rudh CKO
At
V
PECAM1
pSmad2/3
pSmad2/3 MFI (au)
CKO

Figure 1

480

481 **Fig. 1. Rudhira depletion deregulates developmental endothelial TGFβ signaling.** (A) KEGG pathway
482 map indicating TGFβ pathway genes from KEGG database that are deregulated upon *rudhira*
483 depletion in mouse embryonic yolk sac, based on [14]. Genes were mapped based on fold change
484 in *rudhira*$^{-/-}$ yolk sacs in comparison to control to understand pathway regulation. Green:
485 downregulated, Red: upregulated. Blue circles indicate affected genes or processes known to be
486 affected upon Rudhira depletion, from earlier studies. (B) NS and KD SVEC cells, transfected with
487 constitutively active TGFβRI for 24h, were analyzed for Smad2 phosphorylation by Immunoblotting.
488 Graph shows the quantitation of pSmad2/Smad2 levels (N= 3 independent experiments). (C, D)
489 Control (NS), *rudhira* knockdown (KD) and rescued KD (KD + Rudhira-2A-GFP) cells were kept
490 untreated or treated with TGFβ and used for various assays, as indicated. (C) Immunoblot for
491 Smad2/3 and pSmad2. Graph shows the quantitation of pSmad2/Smad2 levels (N= 3 independent
492 experiments). (D) qRT-PCR analysis of *mmp9* and *pai1*, known Smad2/3 targets in ECs (N= 3
493 independent experiments). (E, E') Immunostaining for phosphorylated Smad2/3 in control and
494 *rudhira* conditional knockout *(rudh*^{CKO}*)* embryos at E10.5. Boxed region in the embryonic heart in (E)
495 marking the endocardium and the myocardium are magnified in (E') (N= 3 embryos for each
496 genotype). White dotted line indicates the endocardium. Graph shows the quantitation of pSmad2/3
497 levels (N= 3 independent experiments). Statistical analysis was performed using two-way ANOVA
498 .(A, B, C, D) and student's t-test (E). Error bars indicate standard error of mean (SEM). *$p<0.05$,
499 **$p<0.01$, ***$p<0.001$. Scale bar: (E) 100 µm; (E') 20 µm.

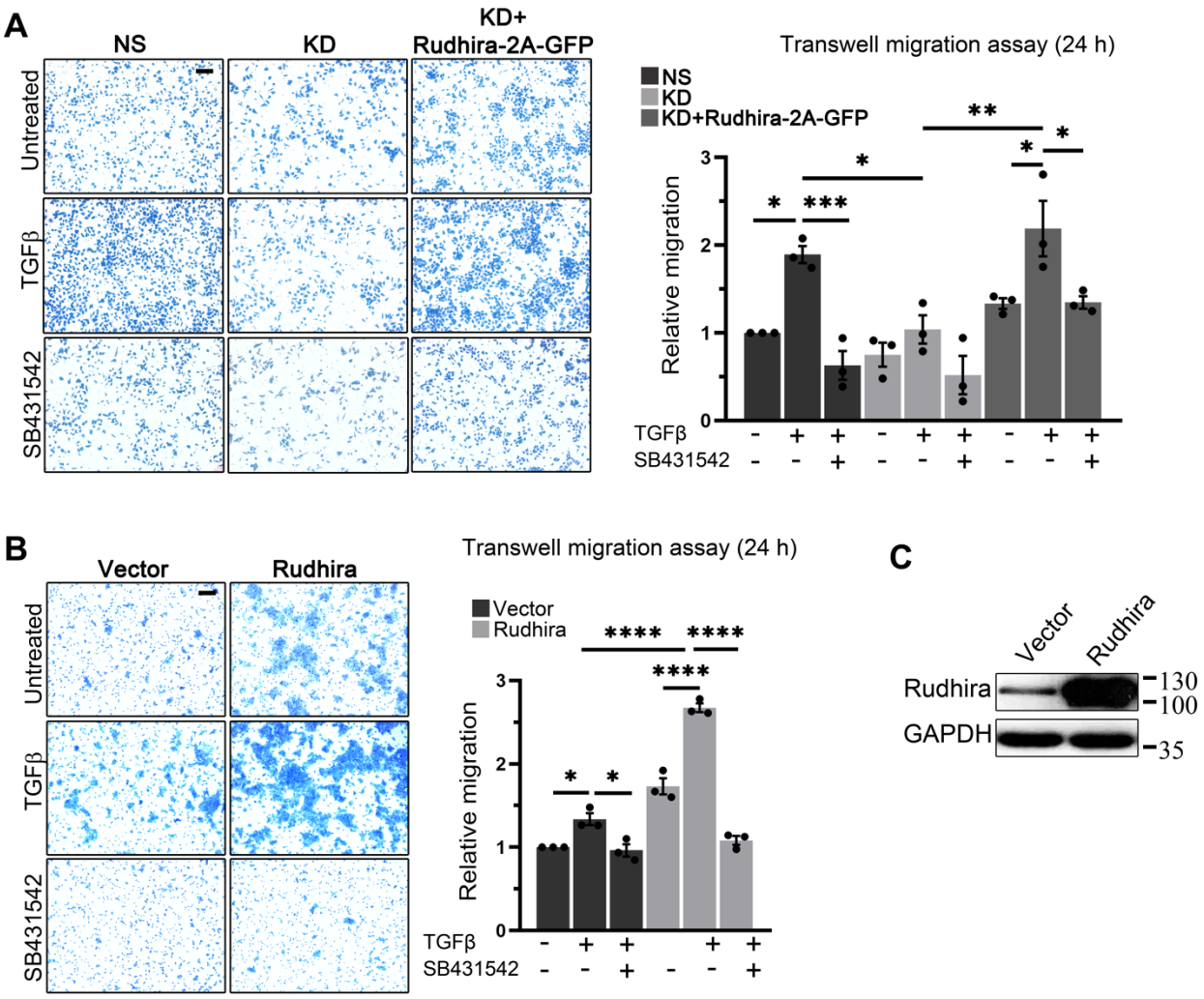

Figure 2

Fig. 2. Rudhira functions downstream of TGFβ receptor activation to promote TGFβ-dependent cell migration. (A) Control (NS), *rudhira* knockdown (KD) and rescued KD (KD + Rudhira-2A-GFP) cells were analyzed for migration rates with or without TGFβ using a transwell migration assay. Graph shows the extent of cell migration as measured by crystal violet absorbance (N= 3 independent experiments). (B, C) HEK293 cells transfected with vector alone or Rudhira were analyzed for migration rates using a transwell migration assay in various conditions, as indicated. Graph shows the extent of cell migration as measured by crystal violet absorbance (N= 3 independent experiments). Statistical analysis was performed using one-way ANOVA. Error bars indicate SEM. Scale bar: (A, B) 100 µm. *p<0.05, **p<0.01, ***p<0.001.

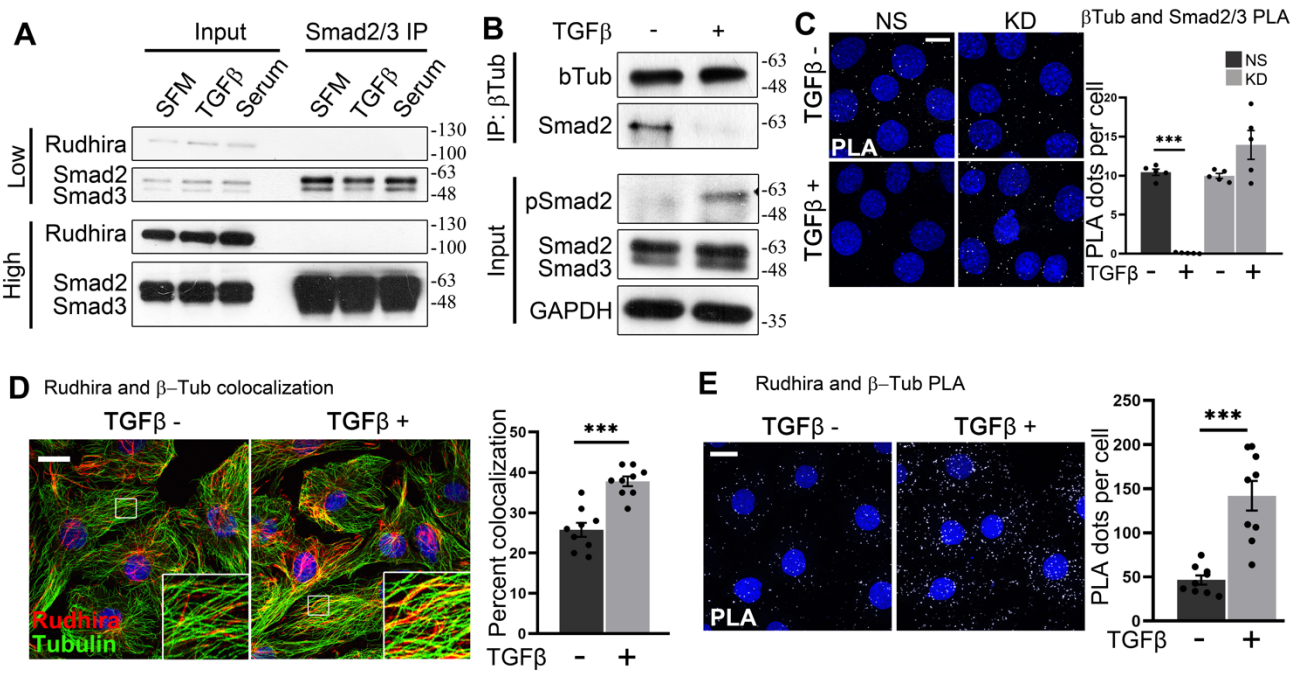

Figure 3

Fig. 3. Rudhira is essential for the release of Smads from microtubules for TGFβ pathway activation. (A) Analysis of interaction between Rudhira, Smad2/3 and MTs by co-immunoprecipitation and immunoblotting, as indicated (N= 3 independent experiments). (B) Loss of Smad-MT interaction on TGFβ stimulation in SVEC cells (N= 3 independent experiments). (C) NS and KD cells were analyzed for MT and Smad2/3 interaction by PLA for Tubulin and Smad2/3 with or without TGFβ treatment. PLA dots represent Smad2/3 and β-tubulin interaction. Graph shows the quantitation of PLA dots per cell (quantitation from >80 cells for two knockdown cell lines from N= 3 independent experiments; also see Fig. S3). (D, E) Association of Rudhira and MTs was analyzed by immunostaining (D) or Proximity Ligation Assay (PLA) (E) for Rudhira and Tubulin with or without TGFβ stimulation in SVEC. PLA dots represent Rudhira and β-tubulin interaction. Graph (D) shows the quantitation of colocalization percentage (quantitation from ~40 cells from 9 images each with or without TGFβ respectively from N= 3 independent experiments) and graph (E) shows the quantitation of PLA dots per cell (quantitation from 86 or 68 cells from 9 images each with or without TGFβ respectively from N= 3 independent experiments). Statistical analysis was performed using one-way ANOVA. Error bars indicate SEM. Scale bar: (C) 20 µm; (D, E) 10 µm. *p<0.05, **p<0.01, ***p<0.001.

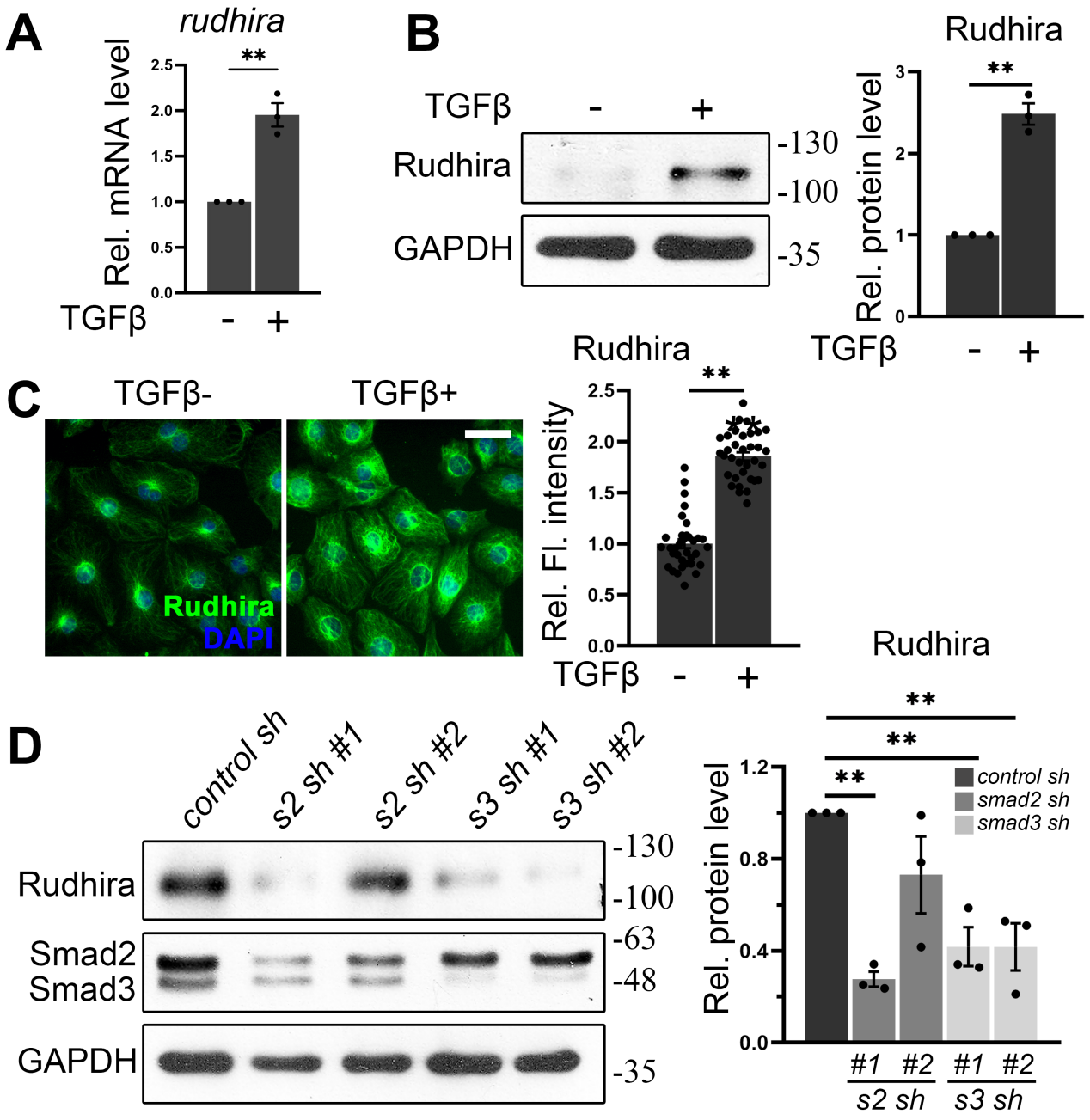

Figure 4

527

528 **Fig. 4. Rudhira is a Smad2/3-dependent target of TGFβ signaling.** (A-C) TGFβ stimulation
529 followed by qRT-PCR (A), immunoblot (B) or immunostaining (C) analysis (quantitation from 34 cells
530 in each condition) of Rudhira levels in SVEC cells. Graphs in (B) and (C) show the quantitation of
531 Rudhira levels with or without TGFβ (N= 3 independent experiments). (D) Analysis of Rudhira levels
532 upon *smad2* or *smad3* knockdown in HEK293T cells by immunoblotting (N= 3 independent
533 experiments). Statistical analysis was performed using one-way ANOVA. Error bars indicate SEM.

534 Scale bar: (C) 10 µm. *$p<0.05$, **$p<0.01$, ***$p<0.001$.

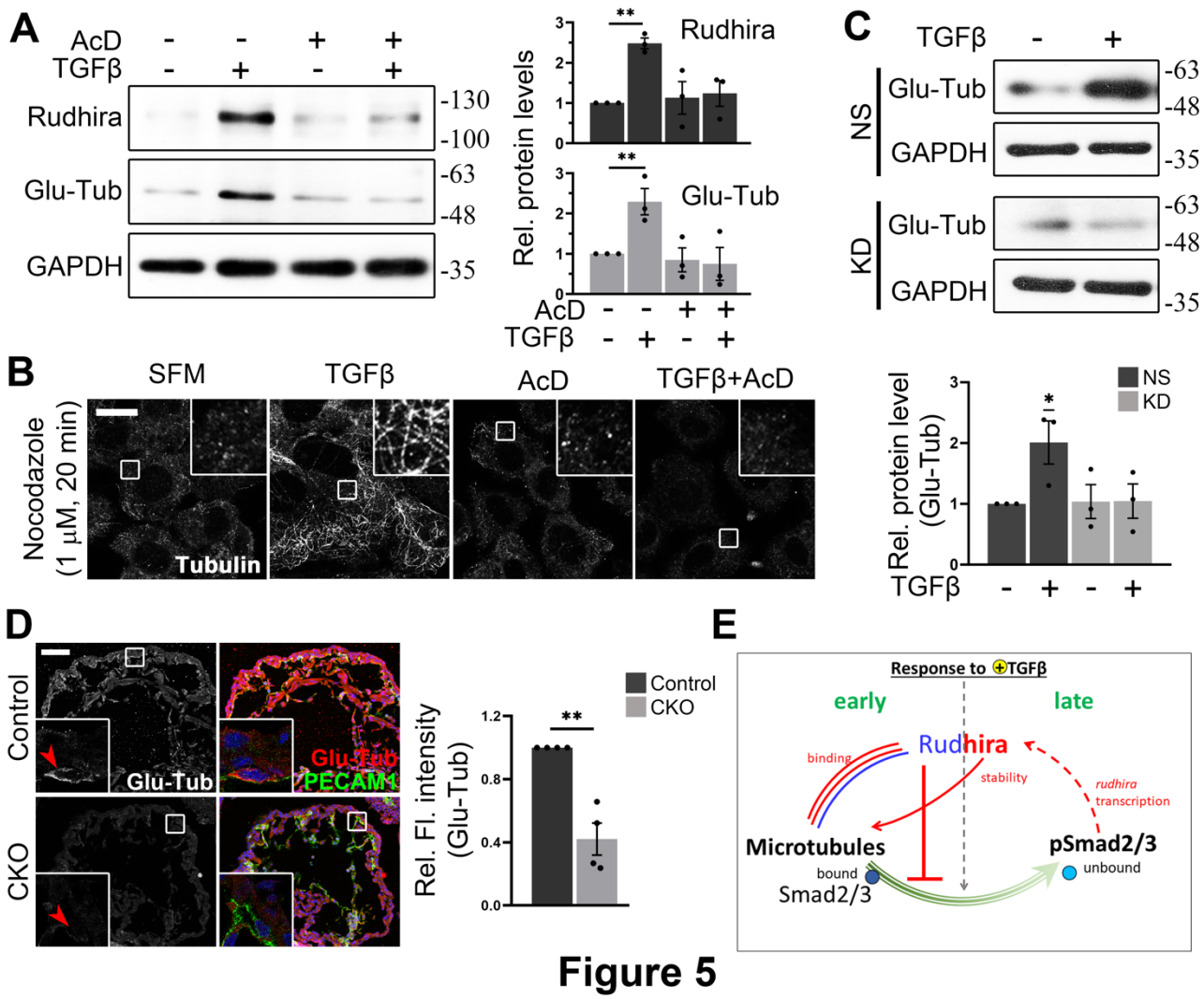

Figure 5

Fig. 5. TGFβ-dependent *rudhira* transcription stabilizes MTs. (A) Analysis of Rudhira levels and MT stability (marked by Glu-Tubulin) upon treatments as indicated, by immunoblotting. Graphs show the quantitation of Rudhira or Glu-Tub levels (N= 3 independent experiments). (B) Analysis of MT resistance to Nocodazole mediated depolymerization at indicated dosage and time (N= 30 cells). (C) MT stability in serum starved NS or KD SVEC cells kept untreated or treated with TGFβ was analyzed by immunoblot for Glu-Tubulin. Graph shows the quantitation of Glu-Tub levels (N= 3 independent experiments). (D) Immunostaining for Glu-Tubulin in control and *rudhira* conditional knockout *(rudh^{CKO})* embryos at E10.5. Endocardium in the heart is marked by PECAM1. Boxed region in the embryonic heart is magnified in the insets. Red arrowheads in the insets mark the PECAM1 positive cells (N= 4 embryos for each genotype). Graph shows the quantitation of Glu-Tub fluorescence intensity in the endocardium. (E) Model depicting cellular and molecular response to

547 TGF addition. Rudhira has an early and a late effect on MTs. Previously known information
548 about Rudhira is shown in blue. Events identified in this study are shown in red or pink. Parallel
549 lines indicate protein- protein interaction. Solid lines indicate direct effects. Dotted lines indicate
550 effects that may be direct or indirect. Arrows indicate positive regulation. Bar-headed line
551 indicates inhibition. Statistical analysis was performed using one-way ANOVA. Error bars indicate
552 SEM. Scale bar: (B) 10 µm; (D) 100 µm. *$p<0.05$, **$p<0.01$, ***$p<0.001$.

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Rudhira-mediated microtubule stability controls TGFβ signaling during mouse vascular development.

Divyesh Joshi[1#], Preeti Jindal[1#], Ronak Shetty[1] and Maneesha S. Inamdar[1,2*]

[1]Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India;[2]Institute for Stem Cell Science and Regenerative Medicine (inStem), Bangalore, India.

Supplementary Figures and Figure legends

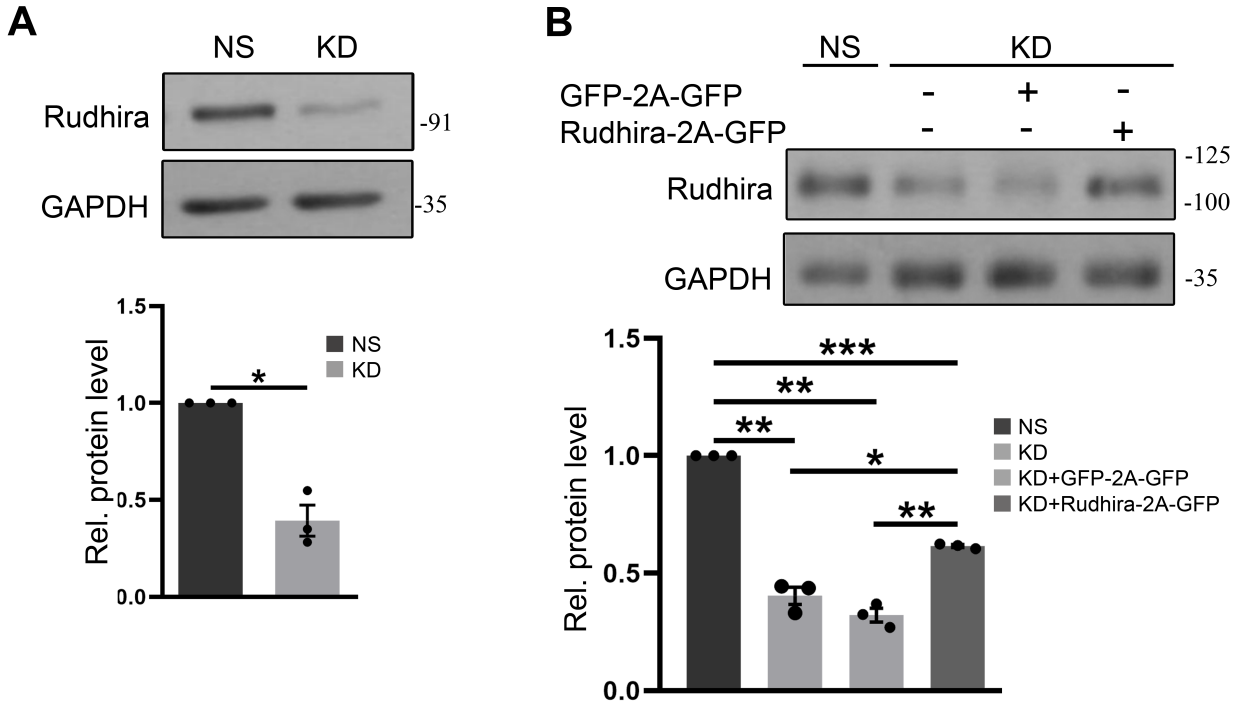

Figure S1

Fig. S1 (related to Fig. 1). Cell line validation. (A, B) Validation of Rudhira knockdown and restoration in SVEC cells by immunoblotting. Statistical analysis was performed using one-sample t-test. Error bars indicate standard error of mean (SEM). *p<0.05, **p<0.01,***p<0.001.

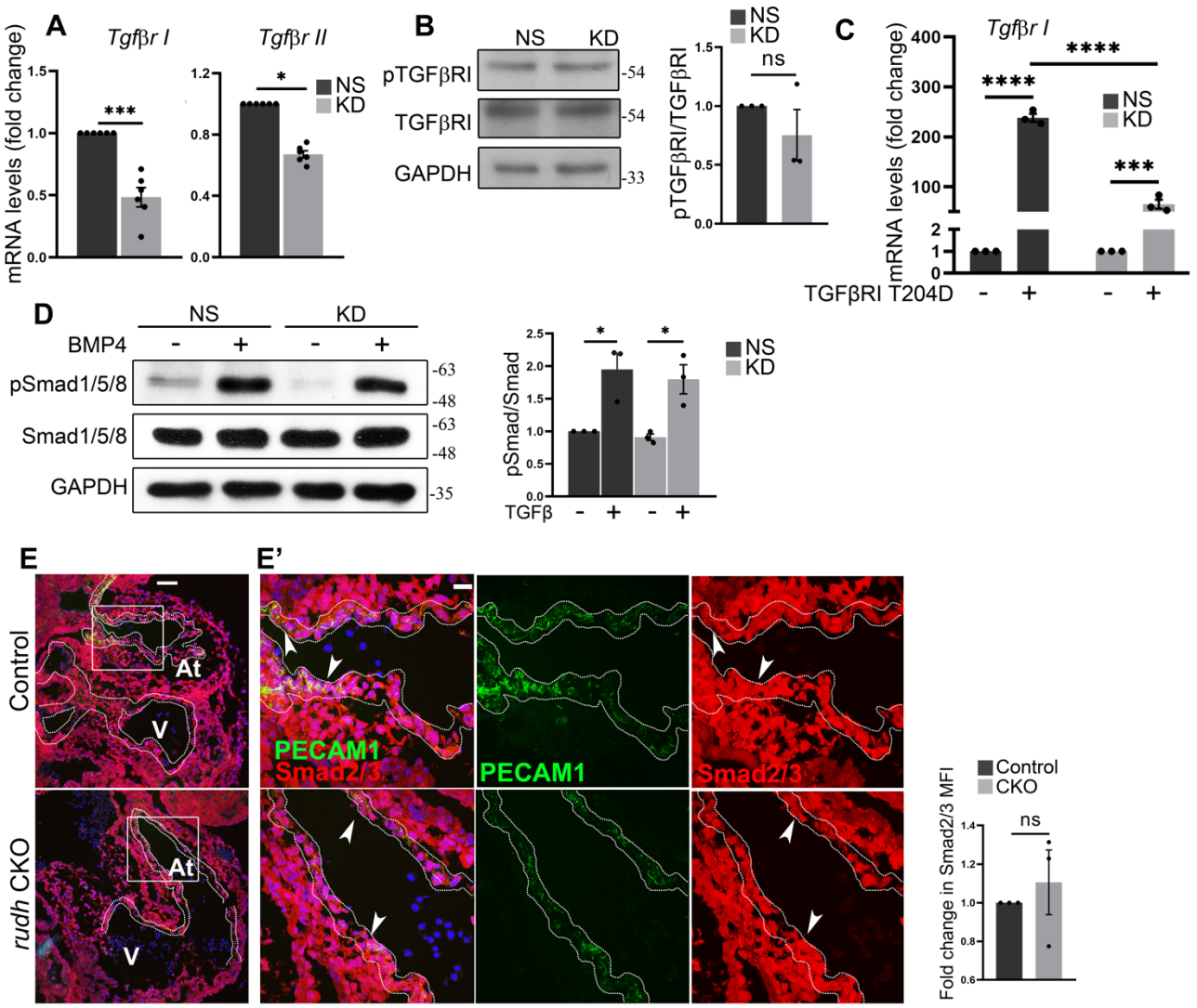

Figure S2

Fig. S2 (related to Fig. 1). Rudhira acts downstream to TGFβ receptors. (A) qRT-PCR analysis of *tgfβrI* and *tgfβrII* in Rudhira knockdown endothelial cells (N= 3 independent experiments). (B) TGFβRI phosphorylation was analyzed using immunoblot technique in SVEC NS and KD. Graph shows the quantitation of pTGFβRI/TGFβRI levels (N= 3 independent experiments). (C) NS and KD SVEC cells, transfected with constitutively active TGFβRI for 24h, were analyzed for total TGFβRI level by qRT-PCR. (D) SVEC control (NS) and knockdown (KD) cells were stimulated by BMP4 and used for immunoblotting of pSmad1/5/8. Graph shows the quantitation of pSmad1/5/8 by Smad1/5/8 levels (N= 3 independent experiments). (E, E') Immunostaining for total Smad2/3 in control and rudhira conditional knockout (rudhCKO) embryos at E10.5. Boxed region in the embryonic heart in (E) marking the endocardium and the myocardium are magnified in (E') (N= 3 embryos for each genotype). White dotted line indicates the endocardium. Graph shows the quantitation of Smad2/3 level (N= 3 independent experiments). Statistical analysis was performed using one-sample t-test.

28 Error bars indicate standard error of mean (SEM). *p<0.05, **p<0.01,***p<0.001, ****p<0.0001.

29 Scale bar: (E) 100 µm; (E') 20 µm.

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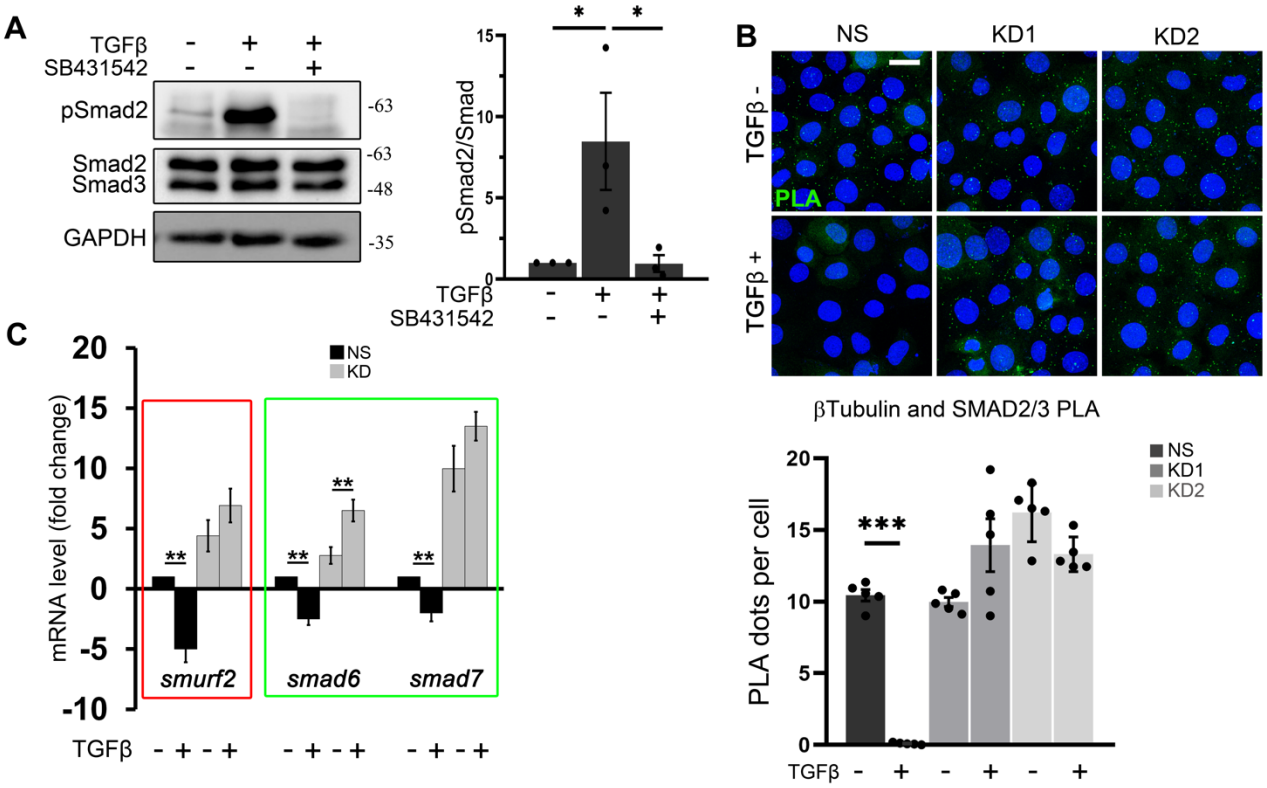


Figure S3

32

33 **Fig. S3 (related to Fig. 1, 2 and 3). Rudhira specifically regulates TGFβ-dependent Smad2/3**

34 **activation.** (A) SVEC cells treated with SB431542 (10µM) for 2h and analyzed for Smad2

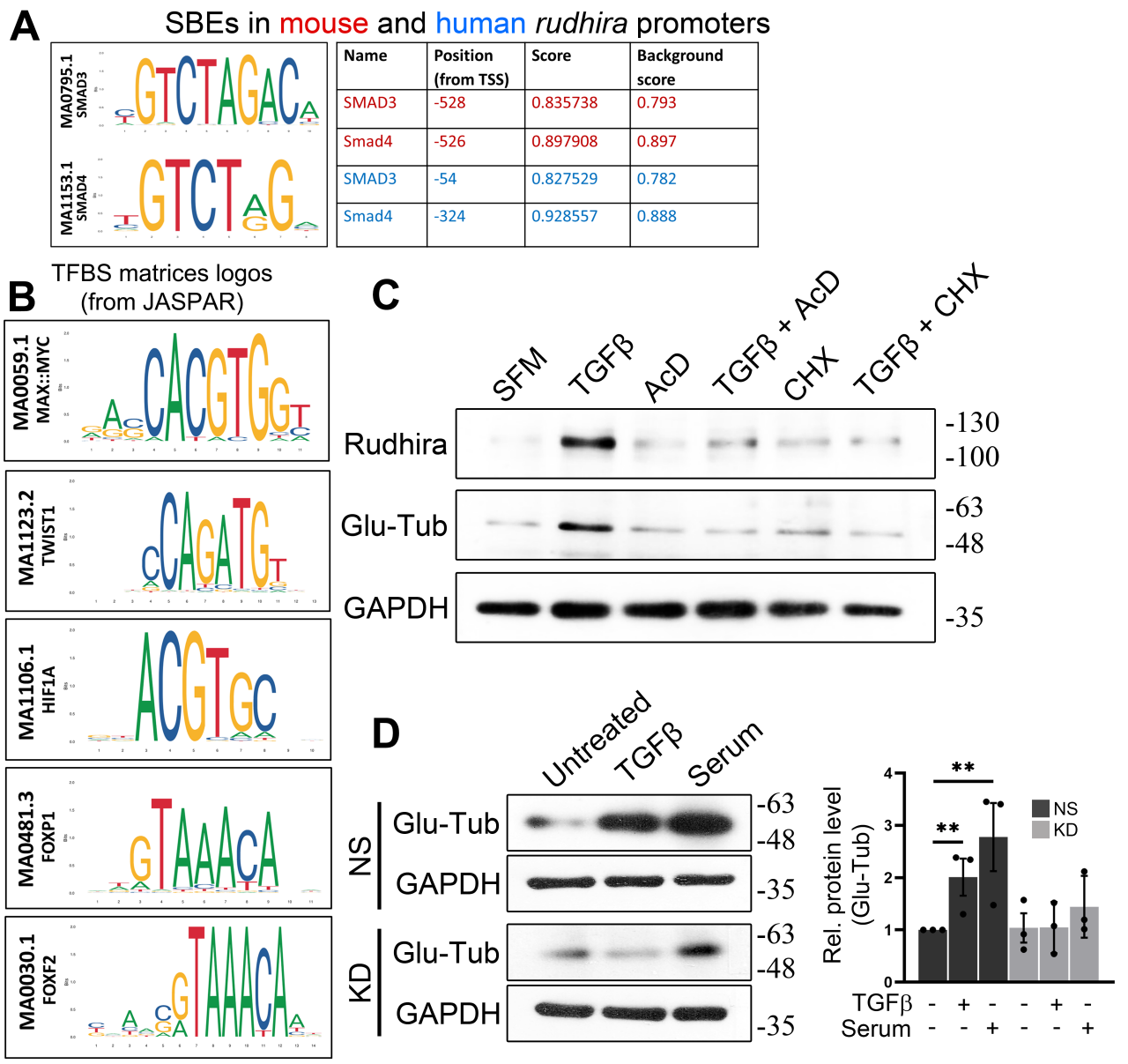
35 phosphorylation by Immunoblotting. (B) NS and two KD SVEC lines (KD1 and KD2) were analyzed for

36 MT-SMAD interaction by PLA for β-Tubulin and Smad2/3 With or without TGFβ treatment (N= 3

37 independent experiments). (C) qRT-PCR analysis of negative regulators of TGFβ pathway (N=3

38 independent experiments). Statistical analysis was performed Using One way ANOVA. Error bars

39 indicate standard error of mean (SEM). Scale bar (B): 20 µm. *p<0.05, **p<0.01, ***p<0.001.



Name	Position (from TSS)	Score	Background score
SMAD3	-528	0.835738	0.793
Smad4	-526	0.897908	0.897
SMAD3	-54	0.827529	0.782
Smad4	-324	0.928557	0.888

Figure S4

Fig. S4 (related to Figs. 4 and 5). TGFβ induces *rudhira* transcription for MT stability. (A) Smad-binding element (SBE) matrix (SMAD3, ID MA0795.1; Smad4, ID MA1153.1) and predicted binding sites in mouse (in red) and human (in blue) *rudhira* promoters, from JASPAR and PSCAN bioinformatics tool. (B) Transcription factor binding sites (TFBS) available from JASPAR and PSCAN bioinformatics tool. (C) Analysis of Rudhira levels and MT stability (marked by Glu-Tubulin) upon treatments as indicated by immunoblotting (N= 3 independent experiments). (D) Analysis of MT stability in serum starved WT and KD cells kept untreated or treated with TGFβ or serum (N= 3 independent experiments).

50 **Supplementary Tables**

51 **Supplementary Table S1. Primers used for qRT-PCR analysis.**

52

Gene	**Forward primer (5' to 3')**	**Reverse primer (5' to 3')**
rudhira	TCCTACATGGAGAGCGTCG	GGAGGCTCATTTCCAGTGC
smurf2	AGACTGGTGTGAGCACATGG	CTTCCTGTTGCGGTATTGCG
smad6	GGGTGAATTCTCAGACGCC	GGTCGTACACCGCATAGAGG
smad7	CGGAAGTCAAGAGGCTGTGT	GACAGCCTGCAGTTGGTTTG
pai1	CTGTGCCCATGATGGCTCAG	ATGAACATGCTGAGGGTGTC
mmp9	GTCCAGACCAAGGGTACAGC	ATACAGCGGGTACATGAGCG
gapdh	GGTGAGGCCGGTGCTGAG	TGATGTCATCATACTTGGCAGG

53

54

55 **Supplementary Table S2. Predicted Transcription factor binding sites in mouse and human**

56 ***rudhira/BCAS3* promoters, obtained from JASPAR bioinformatics tool.**

57

Name	Position (from TSS)	Score	Background score	p-value	Matrix ID (JASPAR)	Strand	Predicted sequence
MAX::MYC	-428	0.959466	0.823	0.00252271	MA0059.1	-	AAGCACGTGGA
MYC	-429	0.959143	0.827	0.00590903	MA0147.3	+	GTCCACGTGCTT
TWIST1	-651	0.988341	0.854	0.00194672	MA1123.2	+	TTTCCAGATGTTC
HIF1A	-427	0.952744	0.849	0.0315803	MA1106.1	+	CCACGTGCTT
FOXP1	-386	0.992493	0.876	0.0124319	MA0481.3	+	ATGTAAACACA
FOXF2	-515	0.932307	0.826	0.0101525	MA0030.1	+	GGAAGGTAAACACA
MAX::MYC	-431	0.965445	0.823	0.00084454	MA0059.1	-	GAGCACGTGGA
MYC	-432	0.97587	0.831	0.00370719	MA0147.3	+	GTCCACGTGCTC
TWIST1	-412	0.88988	0.849	0.19157	MA1123.2	+	GAACCAGCTGTCG
HIF1A	-430	0.963428	0.856	0.0274206	MA1106.1	+	CCACGTGCTC
FOXP1	-389	0.989613	0.864	0.0168508	MA0481.3	+	ATGTAAACAGA
FOXF2	-518	0.932307	0.817	0.0116588	MA0030.1	+	GGAAGGTAAACACA

58

59

60 **Supplementary Table S3. The oligonucleotide sequence of the *smad2* and *smad3* shRNAs.**

61

Gene target	**Oligonucleotide sequence in the shRNA (target sequence in red)**
Smad2 sh#1	CCGGCGATTAGATGAGCTTGAGAAACTCGAGTTTCTCAAGCTCATCTAATCGTTTTTG
Smad2 sh#2	CCGGCCTAAGTGATAGTGCAATCTTCTCGAGAAGATTGCACTATCACTTAGGTTTTTG
Smad3 sh#1	CCGGGCCTCAGTGACAGCGCTATTTCTCGAGAAATAGCGCTGTCACTGAGGCTTTTTG
Smad3 sh#2	CCGGGAGCCTGGTCAAGAAACTCAACTCGAGTTGAGTTTCTTGACCAGGCTCTTTTTG

62