

REFINEMENTS, EXTENSIONS AND GENERALIZATIONS OF THE SECOND KERSHAW'S DOUBLE INEQUALITY

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Abstract. In the paper, the second Kershaw's double inequality concerning the ratio of two gamma functions is refined, extended and generalized elegantly.

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REFERENCES

- [1] M. ABRAMOWITZ AND I. A. STEGUN (EDS), *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, National Bureau of Standards, Applied Mathematics Series **55**, 9th printing, Washington, 1970.
- [2] N. BATIR, *On some properties of digamma and polygamma functions*, J. Math. Anal. Appl. **328** (2007), no. 1, 452–465.
- [3] C. BERG, *Integral representation of some functions related to the gamma function*, Mediterr. J. Math. **1** (2004), no. 4, 433–439.
- [4] P. S. BULLEN, *Handbook of Means and Their Inequalities*, Mathematics and its Applications, Volume 560, Kluwer Academic Publishers, Dordrecht/Boston/London, 2003.
- [5] J. BUSTOZ AND M. E. H. ISMAIL, *On gamma function inequalities*, Math. Comp. **47** (1986), 659–667.
- [6] G. T. CARGO, *Comparable means and generalized convexity*, J. Math. Anal. Appl. **12** (1965), 387–392.
- [7] CH.-P. CHEN, *Monotonicity and convexity for the gamma function*, J. Inequal. Pure Appl. Math. **6** (2005), no. 4, Art. 100; Available online at URL: <http://jipam.vu.edu.au/article.php?sid=574>.
- [8] CH.-P. CHEN AND F. QI, *An alternative proof of monotonicity for the extended mean values*, Austral. J. Math. Anal. Appl. **1** (2004), no. 2, Art. 11; Available online at URL: <http://ajmaa.org/cgi-bin/paper.pl?string=v1n2/V1I2P11.tex>.
- [9] N. ELEZOVIĆ, C. GIORDANO AND J. PEČARIĆ, *The best bounds in Gautschi's inequality*, Math. Inequal. Appl. **3** (2000), 239–252.
- [10] T. ERBER, *The gamma function inequalities of Gurland and Gautschi*, Scand. Actuar. J. **1960** (1961), 27–28.
- [11] W. GAUTSCHI, *Some elementary inequalities relating to the gamma and incomplete gamma function*, J. Math. Phys. **38** (1959), no. 1, 77–81.
- [12] J. D. KEČKIĆ AND P. M. VASIĆ, *Some inequalities for the gamma function*, Publ. Inst. Math. (Beograd) (N. S.) **11** (1971), 107–114.
- [13] D. KERSHAW, *Some extensions of W. Gautschi's inequalities for the gamma function*, Math. Comp. **41** (1983), no. 164, 607–611.
- [14] A. LAFORGIA, *Further inequalities for the gamma function*, Math. Comp. **42** (1984), no. 166, 597–600.
- [15] E. B. LEACH AND M. C. SHOLANDER, *Extended mean values*, Amer. Math. Monthly **85** (1978), 84–90.
- [16] E. B. LEACH AND M. C. SHOLANDER, *Extended mean values II*, J. Math. Anal. Appl. **92** (1983), 207–223.
- [17] Z. PÁLES, *Inequalities for differences of powers*, J. Math. Anal. Appl. **131** (1988), 271–281.
- [18] J. E. PEČARIĆ, F. QI, V. ŠIMIĆ AND S.-L. XU, *Refinements and extensions of an inequality, III*, J. Math. Anal. Appl. **227** (1998), no. 2, 439–448.

- [19] F. QI, *A class of logarithmically completely monotonic functions and application to the best bounds in the second Gautschi-Kershaw's inequality*, J. Comput. Appl. Math. (2009), in press, Available online at URL: <http://dx.doi.org/10.1016/j.cam.2008.05.030>. RGMIA Res. Rep. Coll. **9** (2006), no. 4, Art. 11; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v9n4.asp>.
- [20] F. QI, *A class of logarithmically completely monotonic functions and the best bounds in the first Kershaw's double inequality*, J. Comput. Appl. Math. **206** (2007), no. 2, 1007–1014; Available online at URL: <http://dx.doi.org/10.1016/j.cam.2006.09.005>. RGMIA Res. Rep. Coll. **9** (2006), no. 2, Art. 16, 351–362; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v9n2.asp>.
- [21] F. QI, *A completely monotonic function involving divided difference of psi function and an equivalent inequality involving sum*, ANZIAM J. **48** (2007), no. 4, 523–532. RGMIA Res. Rep. Coll. **9** (2006), no. 4, Art. 5; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v9n4.asp>.
- [22] F. QI, *A completely monotonic function involving divided differences of psi and polygamma functions and an application*, RGMIA Res. Rep. Coll. **9** (2006), no. 4, Art. 8; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v9n4.asp>.
- [23] F. QI, *A new lower bound in the second Kershaw's double inequality*, J. Comput. Appl. Math. **214** (2008), no. 2, 610–616; Available online at URL: <http://dx.doi.org/10.1016/j.cam.2007.03.016>. RGMIA Res. Rep. Coll. **10** (2007), no. 1, Art. 9; Available online at URL:

<http://www.staff.vu.edu.au/rgmia/v10n1.asp>.

- [24] F. QI, *A note on Schur-convexity of extended mean values*, Rocky Mountain J. Math. **35** (2005), no. 5, 1787–1793.
- [25] F. QI, *Certain logarithmically N -alternating monotonic functions involving gamma and q -gamma functions*, Nonlinear Funct. Anal. Appl. **12** (2007), no. 4, 675–685; RGMIA Res. Rep. Coll. **8** (2005), no. 3, Art. 5, 413–422; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v8n3.asp>.
- [26] F. QI, *Generalized abstracted mean values*, J. Inequal. Pure Appl. Math. **1** (2000), no. 1, Art. 4; Available online at URL: <http://jipam.vu.edu.au/article.php?sid=97>. RGMIA Res. Rep. Coll. **2** (1999), no. 5, Art. 4, 633–642; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v2n5.asp>.
- [27] F. QI, *Generalized weighted mean values with two parameters*, R. Soc. Lond. Proc. Ser. A Math. Phys. Eng. Sci. **454** (1998), no. 1978, 2723–2732.
- [28] F. QI, *Logarithmic convexity of extended mean values*, Proc. Amer. Math. Soc. **130** (2002), no. 6, 1787–1796.
- [29] F. QI, *Logarithmic convexities of the extended mean values*, RGMIA Res. Rep. Coll. **2** (1999), no. 5, Art. 5, 643–652; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v2n5.asp>.
- [30] F. QI, *Monotonicity results and inequalities for the gamma and incomplete gamma functions*, Math. Inequal. Appl. **5** (2002), no. 1, 61–67. RGMIA Res. Rep. Coll. **2** (1999), no. 7, Art. 7, 1027–1034; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v2n7.asp>.
- [31] F. QI, *Schur-convexity of the extended mean values*, RGMIA Res. Rep. Coll. **4** (2001), no. 4, Art. 4, 529–533; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v4n4.asp>.
- [32] F. QI, *The best bounds in Kershaw's inequality and two completely monotonic functions*, RGMIA Res. Rep. Coll. **9** (2006), no. 4, Art. 2; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v9n4.asp>.
- [33] F. QI, *The extended mean values: Definition, properties, monotonicities, comparison, convexities, generalizations, and applications*, Cubo Mat. Educ. **5** (2003), no. 3, 63–90. RGMIA Res. Rep. Coll. **5** (2002), no. 1, Art. 5, 57–80; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v5n1.asp>.
- [34] F. QI, *Three classes of logarithmically completely monotonic functions involving gamma and psi functions*, Integral Transforms Spec. Funct. **18** (2007), no. 7, 503–509; Available online at URL: <http://dx.doi.org/10.1080/10652460701358976>. RGMIA Res. Rep. Coll. **9** (2006), Suppl., Art. 6; Available online at URL: [http://www.staff.vu.edu.au/rgmia/v9\(E\).asp](http://www.staff.vu.edu.au/rgmia/v9(E).asp).
- [35] F. QI, J. CAO, AND D.-W. NIU, *Four logarithmically completely monotonic functions involving gamma function and originating from problems of traffic flow*, RGMIA Res. Rep. Coll. **9** (2006), no. 3, Art. 9; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v9n3.asp>.
- [36] F. QI, D.-W. NIU, J. CAO, AND SH.-X. CHEN, *Four logarithmically completely monotonic functions involving gamma function*, J. Korean Math. Soc. **45** (2008), no. 2, 559–573.
- [37] F. QI AND B.-N. GUO, *A class of logarithmically completely monotonic functions and the best bounds in the second Kershaw's double inequality*, J. Comput. Appl. Math. **212** (2008), no. 2, 444–456; Available online at URL: <http://dx.doi.org/10.1016/j.cam.2006.12.022>. RGMIA Res. Rep. Coll. **10** (2007), no. 2, Art. 5; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v10n2.asp>.
- [38] F. QI AND B.-N. GUO, *On Steffensen pairs*, J. Math. Anal. Appl. **271** (2002), no. 2, 534–541. RGMIA Res. Rep. Coll. **3** (2000), no. 3, Art. 10, 425–430; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v3n3.asp>.
- [39] F. QI AND B.-N. GUO, *Wendel-Gautschi-Kershaw's inequalities and sufficient and necessary conditions that a class of functions involving ratio of gamma functions are logarithmically completely monotonic*, RGMIA Res. Rep. Coll. **10** (2007), no. 1, Art. 2; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v10n1.asp>.
- [40] F. QI, B.-N. GUO, AND CH.-P. CHEN, *The best bounds in Gautschi-Kershaw inequalities*, Math. Inequal. Appl. **9** (2006), no. 3, 427–436. RGMIA Res. Rep. Coll. **8** (2005), no. 2, Art. 17, 311–320; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v8n2.asp>.
- [41] F. QI AND S. GUO, *New upper bounds in the second Kershaw's double inequality and its generalizations*, RGMIA Res. Rep. Coll. **10** (2007), no. 2, Art. 1; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v10n2.asp>.
- [42] F. QI, S. GUO AND SH.-X. CHEN, *A new upper bound in the second Kershaw's double inequality and its generalizations*, J. Comput. Appl. Math. (2008), in press; Available online at URL: <http://dx.doi.org/10.1016/j.cam.2007.07.037>.
- [43] F. QI, S. GUO AND B.-N. GUO, *Note on a class of completely monotonic functions involving the polygamma functions*, RGMIA Res. Rep. Coll. **10** (2007), no. 1, Art. 5; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v10n1.asp>.
- [44] F. QI AND Q.-M. LUO, *A simple proof of monotonicity for extended mean values*, J. Math. Anal. Appl. **224** (1998), no. 2, 356–359.

- [45] F. QI, J. SÁNDOR, S. S. DRAGOMIR, AND A. SOFO, *Notes on the Schur-convexity of the extended mean values*, Taiwanese J. Math. **9** (2005), no. 3, 411–420. RGMIA Res. Rep. Coll. **5** (2002), no. 1, Art. 3, 19–27; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v5n1.asp>.
- [46] F. QI AND S.-L. XU, *The function $(b^x - a^x)/x$: Inequalities and properties*, Proc. Amer. Math. Soc. **126** (1998), no. 11, 3355–3359.
- [47] F. QI, S.-L. XU, AND L. DEBNATH, *A new proof of monotonicity for extended mean values*, Internat. J. Math. Math. Sci. **22** (1999), no. 2, 415–420.
- [48] F. QI AND SH.-Q. ZHANG, *Note on monotonicity of generalized weighted mean values*, R. Soc. Lond. Proc. Ser. A Math. Phys. Eng. Sci. **455** (1999), no. 1989, 3259–3260.
- [49] H.-N. SHI, SH.-H. WU, AND F. QI, *An alternative note on the Schur-convexity of the extended mean values*, Math. Inequal. Appl. **9** (2006), no. 2, 219–224. Bùdǎngshì Yǎnjiū Tōngxùn (Communications in Studies on Inequalities) **12** (2005), no. 3, 251–257.
- [50] J. G. WENDEL, *Note on the gamma function*, Amer. Math. Monthly **55** (1948), no. 9, 563–564.
- [51] D. V. WIDDER, *The Laplace Transform*, Princeton University Press, Princeton, 1946.
- [52] A. WITKOWSKI, *Convexity of weighted extended mean values*, RGMIA Res. Rep. Coll. **7** (2004), no. 2, Art. 10; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v7n2.asp>.
- [53] A. WITKOWSKI, *Weighted extended mean values*, Colloq. Math. **100** (2004), no. 1, 111–117. RGMIA Res. Rep. Coll. **7** (2004), no. 1, Art. 6; Available online at URL: <http://www.staff.vu.edu.au/rgmia/v7n1.asp>.
- [54] S.-L. ZHANG, CH.-P. CHEN AND F. QI, *Another proof of monotonicity for the extended mean values*, Tamkang J. Math. **37** (2006), no. 3, 207–209.