

# ON A GEOMETRIC INEQUALITY BY J. SÁNDOR

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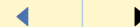
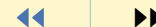
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*Key words:* Triangle, Hayashi's inequality, Hölder's inequality, Gerretsen's inequality, Euler's inequality.  
*Abstract:* In this short note, we sharpen and generalize a geometric inequality by J. Sándor. As applications of our results, we give an alternative proof of Sándor's inequality and solve two conjectures posed by Liu.  
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**Geometric Inequality by J. Sándor**  
Yu-Dong Wu, Zhi-Hua Zhang  
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Title Page

Contents



Page 1 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
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issn: 1443-5756

# Contents

<b>1</b>	<b>Introduction and Main Results</b>	<b>3</b>
<b>2</b>	<b>Preliminary Results</b>	<b>4</b>
<b>3</b>	<b>Proof of the Main Result</b>	<b>7</b>
<b>4</b>	<b>Applications</b>	<b>8</b>
4.1	Alternative Proof of Theorem 1.1 . . . . .	8
4.2	Solution of Two Conjectures . . . . .	8
4.3	Sharpened Form of Above Conjectures . . . . .	10
4.4	Generalization of Inequality (4.3) . . . . .	11
<b>5</b>	<b>Two Open Problems</b>	<b>14</b>



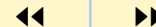
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**Geometric Inequality** by J. Sándor  
Yu-Dong Wu, Zhi-Hua Zhang  
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vol. 10, iss. 4, art. 118, 2009

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Title Page

Contents



Page 2 of 15

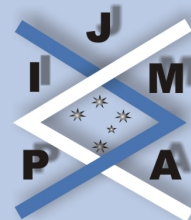
Go Back

Full Screen

Close

journal of **inequalities**  
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## 1. Introduction and Main Results

Let  $P$  be an arbitrary point  $P$  in the plane of triangle  $ABC$ . Let  $a, b, c$  be the lengths of these sides,  $\Delta$  the area,  $s$  the semi-perimeter,  $R$  the circumradius and  $r$  the inradius, respectively. Denote by  $R_1, R_2, R_3$  the distances from  $P$  to the vertices  $A, B, C$ , respectively.

The following interesting geometric inequality from 1986 is due to J. Sándor [8], a proof of this inequality can be found in the monograph [9].

**Theorem 1.1.** *For triangle  $ABC$  and an arbitrary point  $P$ , we have*

$$(1.1) \quad (R_1R_2)^2 + (R_2R_3)^2 + (R_3R_1)^2 \geq \frac{16}{9} \Delta^2.$$

Recently, J. Liu [6] also independently proved inequality (1.1).

In this short note, we sharpen and generalize inequality (1.1) and obtain the following results.

**Theorem 1.2.** *We have*

$$(1.2) \quad (R_1R_2)^2 + (R_2R_3)^2 + (R_3R_1)^2 \geq \frac{a^2b^2c^2}{a^2 + b^2 + c^2}.$$

**Theorem 1.3.** *If*

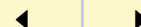
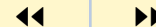
$$k \geq k_0 = \frac{2(\ln 3 - \ln 2)}{3 \ln 3 - 4 \ln 2} \approx 1.549800462,$$

*then*

$$(1.3) \quad (R_1R_2)^k + (R_2R_3)^k + (R_3R_1)^k \geq 3 \left( \frac{4}{9} \sqrt{3} \Delta \right)^k.$$

Title Page

Contents



Page 3 of 15

Go Back

Full Screen

Close



## 2. Preliminary Results

**Lemma 2.1 (Hayashi's inequality, see [7, pp. 297, 311]).** For any  $\triangle ABC$  and an arbitrary point  $P$ , we have

$$(2.1) \quad aR_2R_3 + bR_3R_1 + cR_1R_2 \geq abc,$$

with equality holding if and only if  $P$  is the orthocenter of the acute triangle  $ABC$  or one of the vertices of the triangle  $ABC$ .

**Lemma 2.2 (see [2] and [4]).** For  $\triangle ABC$ , if

$$0 \leq t \leq t_0 = \frac{\ln 9 - \ln 4}{\ln 4 - \ln 3},$$

then we have

$$(2.2) \quad a^t + b^t + c^t \leq 3 \left( \sqrt{3}R \right)^t.$$

**Lemma 2.3.** Let

$$k \geq k_0 = \frac{2(\ln 3 - \ln 2)}{3 \ln 3 - 4 \ln 2} \approx 1.549800462.$$

Then

$$(2.3) \quad \frac{(abc)^k}{\left[ a^{\frac{k}{k-1}} + b^{\frac{k}{k-1}} + c^{\frac{k}{k-1}} \right]^{k-1}} \geq 3 \left( \frac{4}{9} \sqrt{3} \Delta \right)^k.$$

*Proof.* From the well known identities  $abc = 4Rrs$  and  $\Delta = rs$ , inequality (2.3) is equivalent to

$$\frac{(4Rrs)^k}{\left[ a^{\frac{k}{k-1}} + b^{\frac{k}{k-1}} + c^{\frac{k}{k-1}} \right]^{k-1}} \geq 3 \left( \frac{4}{9} \sqrt{3} rs \right)^k,$$

Title Page

Contents

◀◀ ▶▶

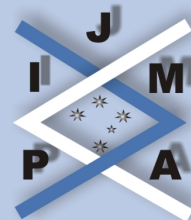
◀ ▶

Page 4 of 15

Go Back

Full Screen

Close



or

$$(2.4) \quad a^{\frac{k}{k-1}} + b^{\frac{k}{k-1}} + c^{\frac{k}{k-1}} \leq 3 \left( \sqrt{3}R \right)^{\frac{k}{k-1}}.$$

It is easy to see that the function

$$f(x) = \frac{x}{x-1}$$

is strictly monotone decreasing on  $(1, +\infty)$ . If we let

$$t = \frac{k}{k-1} = f(k) \quad \left( k \geq k_0 = \frac{2(\ln 3 - \ln 2)}{3 \ln 3 - 4 \ln 2} \right),$$

then

$$0 < f(k) = t \leq \frac{\ln 9 - \ln 4}{\ln 4 - \ln 3} = f(k_0),$$

and inequality (2.4) is equivalent to (2.2).

The proof of Lemma 2.3 is thus complete from Lemma 2.2.  $\square$

**Lemma 2.4 ([3]).** For any  $\lambda \geq 1$ , we have

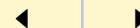
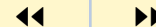
$$(2.5) \quad [R - \lambda(\lambda + 1)r]s^2 + r[4(\lambda^2 - 4)R^2 + (5\lambda^2 + 12\lambda + 4)Rr + (\lambda^2 + 3\lambda + 2)r^2] \geq 0.$$

**Lemma 2.5.** In triangle  $ABC$ , we have

$$a^9 + b^9 + c^9 = 2s[s^8 - 18r(R + 2r)s^6 + 18r^2(21Rr + 7r^2 + 12R^2)s^4 - 6r^3(105r^2R + 240rR^2 + 14r^3 + 160R^3)s^2 + 9r^4(r + 2R)(r + 4R)^3].$$

Title Page

Contents

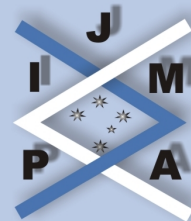


Page 5 of 15

Go Back

Full Screen

Close



*Proof.* The identity directly follows from the known identities  $a + b + c = 2s$ ,  $ab + bc + ca = s^2 + 4Rr + r^2$ ,  $abc = 4Rrs$  and the following identity:

$$\begin{aligned} & a^9 + b^9 + c^9 \\ &= 3a^3b^3c^3 - 45abc(ab + bc + ca)(a + b + c)^4 + 54abc(ab + bc + ca)^2(a + b + c)^2 \\ &\quad - 27a^2b^2c^2(ab + bc + ca)(a + b + c) + (a + b + c)^9 \\ &\quad - 9(ab + bc + ca)(a + b + c)^7 + 9(ab + bc + ca)^4(a + b + c) \\ &\quad - 30(ab + bc + ca)^3(a + b + c)^3 + 18a^2b^2c^2(a + b + c)^3 \\ &\quad + 27(ab + bc + ca)^2(a + b + c)^5 + 9abc(a + b + c)^6 - 9abc(ab + bc + ca)^3. \end{aligned}$$

□

**Lemma 2.6 ([5]).** *If  $x, y, z \geq 0$ , then*

$$x + y + z + 3\sqrt[3]{xyz} \geq 2(\sqrt{xy} + \sqrt{yz} + \sqrt{zx}).$$

**Geometric Inequality** by J. Sándor  
Yu-Dong Wu, Zhi-Hua Zhang  
and Xiao-guang Chu  
vol. 10, iss. 4, art. 118, 2009

Title Page

Contents



Page 6 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
in pure and applied  
mathematics

issn: 1443-5756



### 3. Proof of the Main Result

The proof of Theorem 1.2 is easy to find from the following inequality (3.1) for  $k = 2$  of the proof of Theorem 1.3. Now, we prove Theorem 1.3.

**The proof of Theorem 1.3.** Hölder's inequality and Lemma 2.1 imply for  $k > 1$  that

$$\left[ a^{\frac{k}{k-1}} + b^{\frac{k}{k-1}} + c^{\frac{k}{k-1}} \right]^{\frac{k-1}{k}} \left[ (R_1 R_2)^k + (R_2 R_3)^k + (R_3 R_1)^k \right]^{\frac{1}{k}} \geq a R_2 R_3 + b R_3 R_1 + c R_1 R_2 \geq abc,$$

or

$$(3.1) \quad (R_1 R_2)^k + (R_2 R_3)^k + (R_3 R_1)^k \geq \frac{(abc)^k}{\left[ a^{\frac{k}{k-1}} + b^{\frac{k}{k-1}} + c^{\frac{k}{k-1}} \right]^{k-1}}.$$

Combining inequality (3.1) and Lemma 2.3, we immediately see that Theorem 1.3 is true.  $\square$

Title Page

Contents



Page 7 of 15

Go Back

Full Screen

Close



## 4. Applications

### 4.1. Alternative Proof of Theorem 1.1

From Theorem 1.2, in order to prove inequality (1.1), we only need to prove the following inequality:

$$(4.1) \quad \frac{a^2b^2c^2}{a^2 + b^2 + c^2} \geq \frac{16}{9} \Delta^2.$$

With the known identities  $abc = 4Rrs$  and  $\Delta = rs$ , inequality (4.1) is equivalent to

$$a^2 + b^2 + c^2 \leq 9R^2.$$

This is simply inequality (2.2) for  $t = 2 < t_0$  in Lemma 2.2. This completes the proof of inequality (1.1).

*Remark 1.* The above proof of inequality (1.1) is simpler than Liu's proof [6].

### 4.2. Solution of Two Conjectures

In 2008, J. Liu [6] posed the following two geometric inequality conjectures, (4.2) and (4.3), involving  $R_1, R_2, R_3, R$  and  $r$ .

**Conjecture 4.1.** For  $\triangle ABC$  and an arbitrary point  $P$ , we have

$$(4.2) \quad (R_1R_2)^2 + (R_2R_3)^2 + (R_3R_1)^2 \geq 8(R^2 + 2r^2)r^2,$$

and

$$(4.3) \quad (R_1R_2)^{\frac{3}{2}} + (R_2R_3)^{\frac{3}{2}} + (R_3R_1)^{\frac{3}{2}} \geq 24r^3.$$

Title Page

Contents

◀◀ ▶▶

◀ ▶

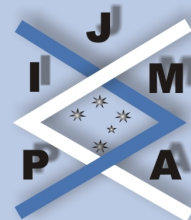
Page 8 of 15

Go Back

Full Screen

Close





*Proof.* First of all, from Gerretsen's inequality [1, pp. 50, Theorem 5.8]

$$s^2 \leq 4R^2 + 4Rr + 3r^2$$

and Euler's inequality [1, pp. 48, Theorem 5.1]

$$R \geq 2r,$$

we have

$$\begin{aligned} 2r^2(4R^2 + 4Rr + 3r^2 - s^2) + (R - 2r)(4R^2 + Rr + 2r^2)r &\geq 0 \\ \iff \frac{16R^2r^2s^2}{2(s^2 - 4Rr - r^2)} &\geq 8(R^2 + 2r^2)r^2. \end{aligned}$$

Using Theorem 1.2 and the known identities [7, pp.52]

$$abc = 4Rrs \quad \text{and} \quad a^3 + b^3 + c^3 = 2s(s^2 - 6Rr - 3r^2),$$

we see that inequality (4.2) holds true.

Secondly, from (3.1), in order to prove inequality (4.3), we only need to prove

$$(4.4) \quad \frac{(abc)^{\frac{3}{2}}}{[a^3 + b^3 + c^3]^{\frac{1}{2}}} \geq 24r^3.$$

With the known identities [7, pp. 52]

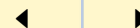
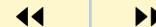
$$abc = 4Rrs \quad \text{and} \quad a^3 + b^3 + c^3 = 2s(s^2 - 6Rr - 3r^2),$$

inequality (4.4) is equivalent to

$$\begin{aligned} (4.5) \quad \frac{(4Rrs)^{\frac{3}{2}}}{[2s(s^2 - 6Rr - 3r^2)]^{\frac{1}{2}}} &\geq 24r^3 \\ \iff 18r^3(4R^2 + 4Rr + 3r^2 - s^2) + R^3(s^2 - 16Rr + 5r^2) \\ &\quad + Rr(R - 2r)(16R^2 + 27Rr - 18r^2) \geq 0. \end{aligned}$$

Title Page

Contents



Page 9 of 15

Go Back

Full Screen

Close



From Gerretsen's inequality [1, pp. 50, Theorem 5.8]

$$16Rr - 5r^2 \leq s^2 \leq 4R^2 + 4Rr + 3r^2$$

and Euler's inequality [1, pp. 48, Theorem 5.1]

$$R \geq 2r,$$

we can conclude that inequality (4.5) holds, further, inequality (4.4) is true.

This completes the proof of Conjecture 4.1. □

**Corollary 4.2.** For  $\triangle ABC$  and an arbitrary point  $P$ , we have

$$(4.6) \quad R_1^3 + R_2^3 + R_3^3 + 3R_1R_2R_3 \geq 48r^3.$$

*Proof.* Inequality (4.6) can directly be obtained from Lemma 2.6 and inequality (4.3). □

### 4.3. Sharpened Form of Above Conjectures

The inequalities (4.2) and (4.3) of Conjecture 4.1 can be sharpened as follows.

**Theorem 4.3.** For  $\triangle ABC$  and an arbitrary point  $P$ , we have

$$(4.7) \quad (R_1R_2)^2 + (R_2R_3)^2 + (R_3R_1)^2 \geq 8(R+r)Rr^2,$$

and

$$(4.8) \quad (R_1R_2)^{\frac{3}{2}} + (R_2R_3)^{\frac{3}{2}} + (R_3R_1)^{\frac{3}{2}} \geq 12Rr^2.$$

*Proof.* The proof of inequality (4.7) is left to the readers. Now, we prove inequality (4.8).

Geometric Inequality by J. Sándor  
Yu-Dong Wu, Zhi-Hua Zhang  
and Xiao-guang Chu

vol. 10, iss. 4, art. 118, 2009

Title Page

Contents



Page 10 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
in pure and applied  
mathematics

issn: 1443-5756



From inequality (2.5) for  $\lambda = 2$  in Lemma 2.4, the well-known Gerretsen's inequality [1, pp. 50, Theorem 5.8]

$$16Rr - 5r^2 \leq s^2 \leq 4R^2 + 4Rr + 3r^2,$$

Euler's inequality [1, pp. 48, Theorem 5.1]

$$R \geq 2r$$

and the known identities [7, pp. 52]

$$abc = 4Rrs \quad \text{and} \quad a^3 + b^3 + c^3 = 2s(s^2 - 6Rr - 3r^2),$$

we obtain that

$$\begin{aligned} (4.9) \quad & [(R - 6r)s^2 + 12r^2(4R + r)] + 3r(4R^2 + 4Rr + 3r^2 - s^2) \\ & + R(s^2 - 16Rr + 5r^2) + r(R - 2r)(4R - 3r) \geq 0 \\ \Leftrightarrow & \frac{(4Rrs)^{\frac{3}{2}}}{[2s(s^2 - 6Rr - 3r^2)]^{\frac{1}{2}}} \geq 12Rr^2 \\ \Leftrightarrow & \frac{(abc)^{\frac{3}{2}}}{[a^3 + b^3 + c^3]^{\frac{1}{2}}} \geq 12Rr^2. \end{aligned}$$

Inequality (4.8) follows by Lemma 2.4.

Theorem 4.3 is thus proved. □

#### 4.4. Generalization of Inequality (4.3)

**Theorem 4.4.** *If  $k \geq \frac{9}{8}$ , then*

$$(4.10) \quad (R_1R_2)^k + (R_2R_3)^k + (R_3R_1)^k \geq 3(4r^2)^k.$$

Title Page

Contents

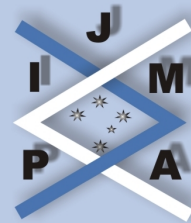


Page 11 of 15

Go Back

Full Screen

Close



*Proof.* From the monotonicity of the power mean, we only need to prove that inequality (4.10) holds for  $k = \frac{9}{8}$ . By using inequality (3.1), we only need to prove the following inequality

$$(4.11) \quad \frac{(abc)^{\frac{9}{8}}}{(a^9 + b^9 + c^9)^{\frac{1}{8}}} \geq 3(4r^2)^{\frac{9}{8}}.$$

From Gerretsen's inequality [1, pp. 50, Theorem 5.8]

$$s^2 \geq 16Rr - 5r^2$$

and Euler's inequality [1, pp. 48, Theorem 5.1]

$$R \geq 2r,$$

it is obvious that

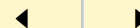
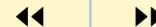
$$\begin{aligned} P = (R - 2r)[4096R^{10} + 12544R^9r + 34992R^8r^2 + 89667R^7r^3 + 218700R^6r^4 \\ + 516132R^5r^5 + 1189728R^4r^6 + 2493180R^3r^7 + 6018624(R - 2r)Rr^8 \\ + 6753456r^{10} + 201204(R^2 - 4r^2)Rr^7] + 2799360r^{11} > 0, \end{aligned}$$

and

$$\begin{aligned} Q = (s^2 - 16Rr + 5r^2)\{R^9(s^2 - 16Rr + 5r^2) \\ + 3R^4r(R - 2r)(16R^5 + 27R^4r + 54R^3r^2 \\ + 108R^2r^3 + 216Rr^4 + 432r^5) + 324r^7[8(R^2 - 12r^2)^2 + 30r^2(R - 2r)^2 \\ + 39Rr^3 + 267r^4]\} + 17496r^7(R^2 - 3Rr + 6r^2)(R^2 - 12Rr + 24r^2)^2 \\ + 3r^2(R - 2r)\{(R - 2r)[256R^9 + 864R^8r + 2457R^2r^2(R^5 - 32r^5) \\ + 6372R^2r^3(R^4 - 16r^4) + 15660R^2r^4(R^3 - 8r^3) + 31320R^2r^5(R^2 - 4r^2) \\ + 220104R^2r^6(R - 2r) + 2618784(R - 2r)r^8 + 51840R^2r^7 + 501120Rr^8] \\ + 687312r^{10}\} > 0. \end{aligned}$$

Title Page

Contents



Page 12 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
in pure and applied  
mathematics

issn: 1443-5756



Therefore, with the fundamental inequality [7, pp.1–3]

$$-s^4 + (4R^2 + 20Rr - 2r^2)s^2 - r(4R + r)^3 \geq 0,$$

we have

$$\begin{aligned} W &= (R^9 - 13122r^9)s^8 + 236196r^{10}(2r + R)s^6 - 236196r^{11}(7r^2 + 12R^2 + 21Rr)s^4 \\ &\quad + 78732r^{12}(105Rr^2 + 160R^3 + 240R^2r + 14r^3)s^2 \\ &\quad - 118098r^{13}(2R + r)(4R + r)^3 \\ &= 13122r^9[s^4 + 9r^3(2R + r)][-s^4 + (4R^2 + 20Rr - 2r^2)s^2 - r(4R + r)^3] \\ &\quad + r^3s^2(R - 2r)P + s^2(s^2 - 16Rr + 5r^2)Q \\ &\geq 0. \end{aligned}$$

Hence, from Lemma 2.4, we get that

$$(4.12) \quad 3 \left( \frac{Rs}{3r} \right)^9 - (a^9 + b^9 + c^9) = \frac{s}{6561r^9} W \geq 0,$$

or

$$(4.13) \quad 3 \left( \frac{Rs}{3r} \right)^9 \geq a^9 + b^9 + c^9.$$

Inequality (4.13) is simply (4.11). Thus, we complete the proof of Theorem 4.4.  $\square$

**Geometric Inequality** by J. Sándor  
Yu-Dong Wu, Zhi-Hua Zhang  
and Xiao-guang Chu

vol. 10, iss. 4, art. 118, 2009

Title Page

Contents

◀◀ ▶▶

◀ ▶

Page 13 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
in pure and applied  
mathematics

issn: 1443-5756

## 5. Two Open Problems

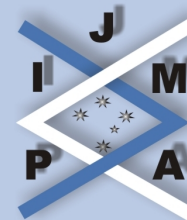
Finally, we pose two open problems as follows.

**Open Problem 1.** For a triangle  $ABC$  and an arbitrary point  $P$ , prove or disprove

$$(5.1) \quad R_1^3 + R_2^3 + R_3^3 + 6R_1R_2R_3 \geq 72r^3.$$

**Open Problem 2.** For a triangle  $ABC$  and an arbitrary point  $P$ , determine the best constant  $k$  such that the following inequality holds:

$$(5.2) \quad (R_1R_2)^{\frac{3}{2}} + (R_2R_3)^{\frac{3}{2}} + (R_3R_1)^{\frac{3}{2}} \geq 12[R + k(R - 2r)]r^2.$$



Geometric Inequality by J. Sándor  
Yu-Dong Wu, Zhi-Hua Zhang  
and Xiao-guang Chu

vol. 10, iss. 4, art. 118, 2009

Title Page

Contents



Page 14 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
in pure and applied  
mathematics

issn: 1443-5756

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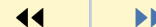
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vol. 10, iss. 4, art. 118, 2009

Title Page

Contents



Page 15 of 15

Go Back

Full Screen

Close

journal of **inequalities**  
in pure and applied  
mathematics

issn: 1443-5756