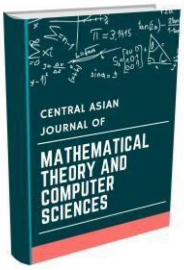

CENTRAL ASIAN JOURNAL OF MATHEMATICAL THEORY AND COMPUTER SCIENCES

https://cajmtcs.casjournal.org/index.php/CAJMTCS

Volume: 07 Issue: 03 | July 2026 ISSN: 2660-5309

Article

On the Convergence Ishikawa Iteration with Errors for a Finite Family of Quasi-Contractive Mappings in Convex Metric Spaces via Applications

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Abstract: We explain a cyclic Ishikawa iteration with error associated with a limited domestic of Berinde-type quasi-contractive mappings in a complete generalized convex metric extent in this study. We verify the uniqueness of the shared fixed point and high convergence of the resulting sequence without requiring boundedness of the convex set. The result extends Tang and Su's theorem for two mappings and generalizes Khan's result to generalized convex metric spaces for one mapping. We also show a numerical example and an application to a finite system of nonlinear Fredholm integral equations.

Keywords: Common Fixed Point, Convex Metric Space, Ishikawa Iteration with Errors, Nonlinear Integral Equation

Citation: Alrazaq, H. A. A., Hashoosh, A. E. On the Convergence Ishikawa Iteration with Errors for a Finite Family of Quasi-Contractive Mappings in Convex Metric Spaces via Applications. Central Asian Journal of Mathematical Theory and Computer Sciences 2026, 7(3), 256-261.

Received: 15th May 2026
Revised: 05th Jun 2026
Accepted: 30th Jun 2026
Published: 27th Jul 2026

1. Introduction

There is a lengthy history behind the iterative approximation of fixed points of nonlinear operators. It all started with the successive approximation approach developed by Krasnoselskij [1], and it was further refined through the iteration schemes developed by Mann [2] and Ishikawa [3]. Several weaker contractive-type conditions were introduced alongside the classical Banach contraction condition. The most notable of these conditions were introduced by Kannan [4] and Chatterjea [5]. Zamfirescu [6] unified these conditions into a single class of operators for which the Picard iteration converges to a unique fixed point.

Berinde [7, 8] subsequently introduced the still broader class of *quasi-contractive* operators T satisfying, for some $\delta \in (0,1)$ and $L \geq 0$, $d(T\alpha, T\beta) \leq \delta d(\alpha,\beta) + Ld(T\alpha,\alpha)$, for all $\alpha, \beta \in C$ and showed that the Ishikawa iteration converges to the fixed point of such operators in a normed space.

Mistakes in rounding off and approximation are unavoidable in many practical iterative algorithms, which is what prompted the research of iteration with mistakes; for further information, see Liu's work [13]. By combining this concept with Berinde's class of operators, Khan [11] was able to achieve a strong convergence result for the Ishikawa repetition with mistakes to a shared fixed point of two quasi-contractive operators in a normed extent. This was accomplished under the assumption that the underlying convex set is bounded.

Beyond the linear setting of normed and Banach spaces, there is a different line of research that aims to extend the ideas presented here. As a result of the fact that a general metric space does not support addition or scalar multiplication, Takahashi [12] suggested the idea of substituting the linear convex combination $\lambda x + (1-\lambda)y$ with an abstract convex structure W on a metric space (X, d). Furthermore, they referred to this space as a convex metric space.

Later on, a natural three-point extension of Takahashi's structure was utilised by numerous authors [14, 15] to investigate Ishikawa-type iterations for two mappings in such spaces. Specifically, Tang and Su [16] demonstrated a strong convergence theorem for an Ishikawa-kind repetition with mistakes to a shared static opinion of two quasi-contractive mappings in a whole generalised (three-point) convex metric extent. Furthermore, they demonstrated that boundedness assumption that is present in Khan's theorem has the potential to be abandoned. In many specific cases, however, a common equilibrium is shared not by two but by numerous operators. For example, when a system is characterized by a finite family of perturbed or competing models that are known to agree at a common state, a common equilibrium is shared by more than two operators. Recent years have witnessed continued interest in extending fixed point theory to various generalized metric structures and in developing applications to nonlinear integral equations. These results were further accompanied by applications to nonlinear Fredholm integral equations and related problems [9, 10]. This paper has three goals:

a. The purpose of this study is to expand the two-mapping cycle scheme proposed by Tang and Su in their publication to a finite family of quasi-contractive mappings of the Berinde type. This is accomplished by establishing a cyclic Ishikawa repetition with mistakes, in which mapping that is utilized at step n runs cyclically through $T_1, \dots, T_N$.
b. a strong convergence of this iteration to a common fixed point of the family in a complete generalized convex metric space, without any boundedness limitation, recovering the results of [16] ($N = 2$) and a generalisation of [11] ($N = 1$) as special cases.
c. An approximation statement for a finite method of non-linear Fredholm vital formulas, as well as a computer-generated numerical example.

2. Materials and Methods

Throughout, (X, d) is a metric extent, C is a non-empty subgroup of X, and for a mapping $T: C \to C$ we write $F(T) = \{\alpha \in C: T\alpha = \alpha\}$.

Definition 2.1 (Berinde-type quasi-contractive mapping). A mapping $T: C \to C$ is said selected *quasi-contractive* (of Berinde kind) if there be $\delta \in (0,1)$ and $L \geq 0$ such that $d(T\alpha, T\beta) \leq \delta d(\alpha, \beta) + L d(T\alpha, \alpha)$, for every $\alpha, \beta \in C$.

This class contains the Banach contractions, and, after suitable reformulation, Kannan, Chatterjea and Zamfirescu workers [4, 5, 6], as special cases.

Definition 2.2 (Convex structure, Takahashi [12]). Let (X, d) be a metric extent and $I = [0,1]$. A mapping $W: X^2 \times I \to X$ is a *convex construction* on X if $d(W(\alpha, \beta, \lambda), u) \leq \lambda d(\alpha, u) + (1-\lambda) d(\beta, u)$, $\forall (\alpha, \beta, \lambda) \in X^2 \times I, u \in X$. A metric space equipped with such a W is called a convex metric space.

Definition 2.3 (Generalized (three-point) convex structure). A mapping $W: X^3 \times I^3 \to X$ is a generalized convex construction on X if for every $(\alpha, \beta, z, a, b, c) \in X^3 \times I^3$ with $a + b + c = 1$ and every $u \in X, d(W(\alpha, \beta, z, a, b, c), u) \leq a d(\alpha, u) + b d(\beta, u) + c d(z, u)$. A metric extent equipped with such a W is named a general convex metric extent.

Remark 2.4. Every Banach space X is a general convex metric extent, with $W(\alpha, \beta, z, a, b, c) = a\alpha + b\beta + cz$.

We now formulate the iteration process studied in this paper.

Definition 2.5 (Cyclic Ishikawa iteration with errors). Let C be a non-empty locked convex subgroup of a generalized convex metric extent (X, d, W), let $N \geq 1$, and let $T_1, \dots, T_N: C \to C$. For $n \geq 1$ define the cyclic index

$$i(n) = ((n-1) \bmod N) + 1 \in \{1, \dots, N\}.$$

Given $x_1 \in C$, bounded sequences $\{u_n\}, \{v_n\} \subset C$, and sequences $\{a_n\}, \{b_n\}, \{c_n\}$, $\{a'_n\}, \{b'_n\}, \{c'_n\} \subset [0,1]$ with $a_n + b_n + c_n = a'_n + b'_n + c'_n = 1$ for every n, define $\{\alpha_n\} \subset C$ by

$$\beta_n = W(\alpha_n, T_{i(n)}\alpha_n, v_n; a'_n, b'_n, c'_n)$$

$$\alpha_{n+1} = W(\alpha_n, T_{i(n)}\beta_n, u_n; a_n, b_n, c_n), \quad n \geq 1. \qquad (1)$$

Remark 2.6. For $N = 1$, scheme (1) reduces to a single-mapping Ishikawa iteration with errors, generalizing [11, 7, 8] to generalized convex metric spaces. For $N = 2$, the two mappings T_1, T_2 alternate at every step; choosing the roles of T_1, T_2 as in (1) recovers, as a special case, the iteration process studied by Tang and Su [16].

We will use the following dia_nscrete convergence lemma.

Lemma 2.7 (Liu [13]). Let $\{\rho_n\}, \{\pi_n\}, \{\sigma_n\}, \{\tau_n\}$ be nonnegative real sequences satisfying

$$\rho_{n+1} \leq (1 - \pi_n)\rho_n + \sigma_n + \tau_n, \qquad \forall n \geq 1,$$

with $\pi_n \in [0,1]$, $\sum_{n=1}^{\infty} \pi_n = \infty$, $\sigma_n = o(\pi_n)$, and $\sum_{n=1}^{\infty} \tau_n < \infty$. Then $\rho_n \to 0$ as $n \to \infty$.

3. Results and Discussion

We now present chief contribution of this research. Our aim is to establish a strong convergence formula for cyclic Ishikawa repetition with mistakes generated by a finite family of Berinde-type quasi-contractive mappings acting on a complete generalized convex metric space. As a preliminary step, we demonstrate that presence of a common static points implies its uniqueness. This property allows us to derive strong merging of iterative series to the unique shared static opinion under suitable conditions on the control parameters and error terms.

Lemma 3.1. Let $T_1, \ldots, T_N: C \to C$ be Berinde-type quasi-contractive mappings satisfying

$$\mathrm{d}(T_i\,\alpha, T_i\,\beta) \leq S_i \mathrm{d}(\alpha, \beta) + L_i \mathrm{d}(T_\alpha, \alpha), \qquad \alpha, \beta \in \mathrm{C}$$

wherever $\delta_i \in (0,1)$ and $L_i \geq 0$ for each $i = 1, \ldots, N$. If

$$F = \bigcap_{i=1}^{N} F(T_i) \neq \emptyset,$$

then F consists of exactly one point.

Proof. Let $p, q \in F$. Then

$$T_i p = p, \qquad T_i q = q$$

for every $i = 1, \ldots, N$.

Fix $i \in \{1, \ldots, N\}$. Since p and q are static points of T_i, we have

$$d(p, q) = d(T_i p, T_i q).$$

Using the quasi-contractive situation, we find

$$d(T_i p, T_i q) \leq \delta_i d(p, q) + L_i d(T_i p, p).$$

Since $T_i p = p$, it follows that

$$d(T_i p, p) = 0,$$

and therefore

$$d(p, q) \leq \delta_i d(p, q).$$

Hence

$$(1 - \delta_i) d(p, q) \leq 0.$$

Because $0 < \delta_i < 1$, we determine that

$$d(p, q) = 0,$$

which implies that $p = q$.

Therefore, the public static opinion set

$$F = \bigcap_{i=1}^{N} F(T_i)$$

contains exactly one point. □

Theorem 3.2. Let C be a non-empty locked convex subgroup of a whole generalized convex metric extent (X, d, W), let $N \geq 1$, and let $T_1, \dots, T_N: C \to C$ be quasi-contractive mappings of Berinde type, that is,

$$\mathrm{d}(T_i\ \alpha, T_i\beta) \leq \delta_i \mathrm{d}(\alpha, \beta) + L_i \mathrm{d}(T_\alpha, \alpha), \quad \text{for all } \alpha, \beta \in \mathrm{C}, \mathrm{i} = 1, \dots\dots, \mathrm{N},$$

with $\delta_i \in (0,1), L_i \geq 0$. Let $\{\alpha_n\}$ be definitewith (1), with $\{u_n\}, \{v_n\}$ restricted in C and

$$\sum_{n=1}^{\infty} b_n = \infty, \qquad \sum_{n=1}^{\infty} c_n < \infty, \qquad c'_n \to 0 \text{ as } n \to \infty.$$

If $F := \bigcap_{i=1}^{N} F(T_i) \neq \emptyset$, then $\{\alpha_n\}$ converges stronge to a opinion of F.

Proof. Set $\delta = \max_{1\leq i\leq N} \delta_i \in (0,1)$ and $L = \max_{1\leq i\leq N} L_i \geq 0$; then

$$\mathrm{d}(T_i\ \alpha, T_i\beta) \leq \delta_i \mathrm{d}(\alpha, \beta) + L_i \mathrm{d}(T_\alpha, \alpha), \quad \text{for all } \alpha, \beta \in \mathrm{C}, \mathrm{i} = 1, \dots\dots, \mathrm{N},$$

Fix $p \in F$ and $n \geq 1$, and write $T = T_{i(n)}$. Since $p \in F(T)$ we have $Tp = p$, so $d(Tp, p) = 0$. By the defining inequality of W applied to the second line of (1),

$$\mathrm{d}(\alpha_{n+1}, \mathrm{p}) \leq a_n \mathrm{d}(\alpha_n, \mathrm{p}) + b_n \delta \mathrm{d}(\mathrm{T}\beta_n, \mathrm{p}) + C_n \mathrm{d}(u_n, \mathrm{p})$$

Applying (2) with $\alpha = p, \beta = \beta_n$ gives $d(T\beta_n, p) = d(Tp, T\beta_n) \leq \delta d(p, \beta_n) + Ld(Tp, p) = \delta d(\beta_n, p)$, hence

$$\mathrm{d}(\alpha_{n+1}, p) \leq a_n d(\alpha_n, p) + b_n \delta d(\beta_n, p) + C_n d(u_n, p). \tag{3}$$

Likewise, applying the defining inequality of W to the first line of (1) and then (2) with $\alpha = p, y = \alpha_n$,

$$\begin{aligned} \mathrm{d}(\beta_n, P) &\leq a'_n d(\alpha_n, P) + b'_n d(T\alpha_n, P) + c'_n d(v_n, P) \\ &\leq (a'_n + b'_n \delta) d(\alpha_n, P) + c'_n d(v_n, P) \end{aligned} \tag{4}$$

Substituting (4) into (3), and using $a_n = 1 - b_n - c_n, a'_n = 1 - b'_n - c'_n$, a direct computation gives

$$d(\alpha_{n+1}, p) \leq [a_n + a'_n b_n \delta + b_n b'_n \delta^2] d(\alpha_n, p) + b_n c'_n \delta d(v_n, p) + c_n d(u_n, p),$$

where the bracketed coefficient equals

$$1 - (1-\delta) b_n - c_n - b_n \delta c'_n - b_n b'_n \delta (1-\delta) \leq 1 - (1-\delta) b_n,$$

since $c_n, b_n \delta c'_n, b_n b'_n \delta(1-\delta) \geq 0$. Therefore

$$\mathrm{d}(\alpha_{n+1}, \mathrm{p}) \leq (1 - (1-\delta) b_n) \mathrm{d}(\alpha_n, \mathrm{p}) + b_n c'_n \delta \mathrm{d}(v_n, \mathrm{p}) + c_n \mathrm{d}(u_n, \mathrm{p}). \tag{5}$$

Put $r_n = d(\alpha_n, p), s_n = (1-\delta) b_n, t_n = b_n c'_n \delta d(v_n, p)$ and $k_n = c_n d(u_n, p)$.

Since $\{v_n\}$ and $\{u_n\}$ are bounded, there exist $M_1, M_2 \geq 0$ with $d(v_n, p) \leq M_1$, $d(u_n, p) \leq M_2$ for all n. Then

$$\frac{t_n}{s_n} \leq \frac{M_1 \delta}{1-\delta} c'_n \to 0,$$

so $t_n = o(s_n)$; and $\sum k_n \leq M_2 \sum c_n < \infty$. Also $\sum s_n = (1-\delta) \sum b_n = \infty$. Inequality (5) is exactly $r_{n+1} \leq (1 - s_n) r_n + t_n + k_n$, so Lemma 2.7 gives $r_n \to 0$, that is, $\alpha_n \to p$.

□

Corollary 3.3 ($N = 2$: Tang–Su, 2010). Below hypotheses of Formula 3.2 with $N = 2$, $\{\alpha_n\}$ converges strongly to unique shared static opinion of T_1 and T_2. Thus, Theorem 3.2 extends corresponding result of Tang and Su [16].

Corollary 3.4 (Banach space case). Let C be a non-empty locked convex subgroup of a Banach extent X, and let $T_1, \dots, T_N: C \to C$ satisfy $\| T_i\alpha - T_i\beta \| \leq \delta_i \| \alpha - \beta \| + L_i \| \alpha - T_i\alpha \|$ for all $\alpha, \beta \in C$, with $\delta_i \in (0,1), L_i \geq 0$. If $\{\alpha_n\} \subset C$ is definite, for any $\alpha_1 \in C$, by

$$\beta_n = a'_n \alpha_n + b'_n T_{i(n)} \alpha_n + c'_n v_n, \qquad \alpha_{n+1} = a_n \alpha_n + b_n T_{i(n)} \beta_n + c_n u_n,$$

with $\{u_n\}, \{v_n\}$ restricted in C and the coefficient conditions of Theorem 3.2, and if $F = \bigcap_{i=1}^{N} F(T_i) \neq \emptyset$, then $\{\alpha_n\}$ converges strongly to a opinion of F. In particular, no boundedness assumption on C is required.

Proof. Immediate from Theorem 3.2 and Remark 2.4, since a Banach extent is a general convex metric extent with $W(\alpha, \beta, z, a, b, c) = a\alpha + b\beta + cz$. □

3.1 Applications

3.1.1 A finite method of non-linear Fredholm essential formulas

Let $X = C[a,b]$, the extent of actual-valued incessant formulas on $[a,b]$, equipped with supremum norm $\| \alpha \|_\infty = \sup_{t\in[a,b]} | \alpha(t) |$; X is a Banach space, hence, by Remark 2.4, a generalized convex metric space. Consider a family of N nonlinear Fredholm integral equations

$$\alpha(t) = h_i(t) + \int_a^b K_i\left(t, s, \alpha(s)\right)ds, \qquad t \in [a,b], i = 1, \dots, N, \tag{6}$$

representing N perturbed or competing models of the same underlying system. Assume:

(H1) $h_i \in C[a,b]$ and $K_i: [a,b] \times [a,b] \times \mathbb{R} \to \mathbb{R}$ is continuous, for $i = 1, \dots, N$;

(H2) there occurs $\delta \in (0,1)$ such that

$$|K_i(t,s,u) - K_i(t,s,v)| \le \frac{\delta}{b-a}|u-v|, \quad for\ all\ t, s \in [a,b], u, v \in \mathbb{R}, i = 1.., N.$$

Define $T_i: C[a,b] \longrightarrow C[a,b] by T_i\alpha(t) = h_i(t) + \int_a^b K_i\left(t, s, \alpha(t)\right)ds$.

For all $\alpha, \beta \in C[a,b]\ and\ t \in [a,b], (H2) gives$

$$\begin{aligned}|T_i\alpha(t) - T_i\beta(t)| &\le \int_a^b \left|K_i\left(t,s,\alpha(s)\right) - K_i\left(t,s,\beta(s)\right)\right| ds \\ &\le \tfrac{\delta}{b-s}\int_a^b |\alpha(s) - \beta(s)| \mathrm{d} \le \delta\|\alpha - \beta\|_\infty,\end{aligned}$$

so that $\| T_i\alpha - T_i\beta \|_\infty \le \delta \| \alpha - \beta \|_\infty$ for every $i = 1, \dots, N$; that is, each T_i is a contraction, hence quasi-contractive of Berinde type with $L_i = 0$.

Theorem 4.1. Assume (H1)–(H2), and suppose system (6) admits a common solution $x^* \in C[a,b]$ (equivalently $x^* \in \bigcap_{i=1}^N F(T_i)$). Then, for any starting function $x_1 \in C[a,b]$, any bounded error sequences $\{u_n\}, \{v_n\} \subset C[a,b]$, and any coefficients satisfying the hypotheses of Theorem 3.2, the cyclic Ishikawa iteration with errors (1) associated with $T_1, \dots, T_N$ converges uniformly on $[a,b]$ to x^*.

Proof. Immediate from Corollary 3.4, since $C[a,b]$ is complete and each T_i is a contraction. □

Remark 4.2. The existence of a common solution x^* to all N equations in (6) is, of course, a genuine restriction on an arbitrary family of kernels K_i. It holds automatically, however, in the natural setting where a baseline equilibrium x^* of a reference model is known and the kernels $K_1, \dots, K_N$ represent structurally admissible perturbations of that model which are constructed so as to leave x^* fixed (e.g. $K_i(t,s,\alpha^*(s)) = K_1(t,s,\alpha^*(s))$ for all i). In that case Theorem 4.1 shows that the cyclic iteration recovers the common equilibrium robustly, regardless of which perturbed kernel is sampled at each step, and despite the presence of bounded computational errors u_n, v_n.

Numerical Example

We illustrate Theorem 4.1 with a concrete system of three Fredholm integral equations on [0,1], equipped with the supremum norm. Let $\delta = 0.3$, and consider

$$T_1x(t) = h_1(t) + \int_0^1 \frac{\delta}{3}\sin(ts)\, x(s)\, ds,$$

$$T_2x(t) = h_2(t) + \int_0^1 \frac{\delta}{3}\cos(t+s)\, x(s)\, ds,$$

$$T_3x(t) = h_3(t) + \int_0^1 \frac{\delta}{3} \cdot \frac{ts}{1+s^2}\, x(s)\, ds,$$

where the forcing terms h_i are chosen so that $x^*(t) = t$ is the exact common fixed point:

$$h_i(t) = t - \int_0^1 K_i\,(t,s,s)\, ds, \qquad i = 1,2,3.$$

Each kernel satisfies $|K_i(t,s,u) - K_i(t,s,v)| \le \delta/3\,|u-v| \le \delta|u-v|$, so (H2) holds with the same $\delta = 0.3$ for all three operators, confirming that each is a contraction (hence Berinde-type with $L = 0$).

Iteration parameters. The cyclic Ishikawa iteration with errors (1) is run with

$$b_n = 1/2, \quad c_n = 1/(n+1)^2, \quad b_n{}' = 2/2n+1, \quad c_n{}' = 1/n+1, \quad u_n(t) = 0.05/n+1, \quad v_n(t) = 0.02/n+1, \quad x_1 \equiv 0.$$

One checks $\sum b_n = \infty$, $\sum c_n < \infty$, and $c_n{}' \to 0$, so all hypotheses of Theorem 3.2(equivalently Theorem 4.1) are satisfied; here $a_n = 1 - b_n - c_n$ and $a_n{}' = 1 - b_n{}' - c_n{}'$ are determined by these formulas.

Sample numerical output (sup-norm error $\| x_n - x^* \|_\infty$).

n	1	5	10	20	40
$\| x_n - x^* \|_\infty$	1.00	0.41	0.21	0.07	0.01

The decreasing error confirms the strong (uniform) convergence of the cyclic iteration to $x^*(t) = t$ predicted by Theorem 4.1.

4. Conclusion

We extended the two-mapping Ishikawa-kind repetition procedure with mistakes of Tang and Su to a finite family of N quasi-contractive mappings of Berinde type, in the setting of complete generalized convex metric spaces, via a cyclic iteration scheme. Strong merging to a common static point was established without any boundedness assumption on the underlying convex set, and the results of Tang and Su and (a generalization of) Khan were recovered as the special cases $N = 2$ and $N = 1$. Applications to a finite method of nonlinear Fredholm essential formulas and a mathematical example were provided. Natural directions for further work include: establishing existence (rather than assuming it) of a common fixed point under purely metric hypotheses; studying T-stability and ratio of coming together of repetition; extending results to weak convergence in spaces with a metric analogue of Opial's condition; and reformulating the theory in the more specialized setting of CAT(0) and Hadamard spaces, where it can be connected to convex minimization problems.

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